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From silence to Agency: Rewriting the History of Feminism

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***Abstract*—Since past few centuries "Feminism" as a term has evolved in people's lives, resulting in promoting women empowerment and the fundamental rights they deserve. This paper examines the struggle of women through centuries fighting for their basic rights to make a life for themselves, also examining how the historiography of the term feminism has shifted over the past few centuries. Beginning with an account of women's historical exclusion from formal political, legal, and scholarly life, the paper accentuates how the successive waves of feminist activities have globally increased. This paper also traces the shift by which feminist scholarships move. As we go deeper into the study, we would be able to examine the true importance of feminism even in the modern society and what great importance it holds.**

***Index Terms*—Feminism, rights, gender equality, revolution, stereotypes.**

I. INTRODUCTION

A look out through history, feminism as a discipline is quite majorly defined as a radical notion that women are people. Feminism brings many things to philosophy as well not only a variety of particular moral and political claims, but ways of asking and answering questions, critiques of mainstream philosophical views and methods. The term 'Feminism' has many different uses as its meanings are often contested. From early campaigns for women's suffrage and property rights to contemporary discussions surrounding workplace equality, reproductive rights, education, representation, and intersectionality, feminism has continued to expand its scope while remaining a pursuit of gender equality. For generations, the feminist movements has forged ahead advocating for women's rights.

This paper argues that the history of feminism cannot be told simply as a chronology of law passed and rights won, it must instead be understood as a process of historical rewriting of events that shape the world women live in today. Through the historical data and evidences this paper defines women's struggles and fights they have fought even to secure basic rights in the society may it be French Revolution 1789 that began the democratic federation to the Covid 19 pandemic feminism has truly made an exceptional shift of not only the lived experience of women across centuries but

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the methodological shift historians have undergone in how they recover and interpret that entire experience.

II. THE DAWN OF FEMINISM (FIRST WAVE, C. 1848 - 1920)

The First Wave of Feminism was a period of feminist activity and thought that occurred during the 19th and 20th century, particularly securing women's right to vote (suffrage). Spanning the late 1800s to the early 1900s primarily in the United States and United Kingdom.

The movement mainly developed due to several factors, that women during that time went through majorly, factors like ; political exclusion, economic dependence upon their fathers, brothers or any male figure they are associated with, lack of educational opportunities in the society compared to the men, no propertied rights given, unequal marriage law, and also the influence of democratic ideals ("stating all humans are equal"). All these factors eventually led to the major outbreak of Te Seneca Falls Convention (1848), New York eventually leading to the declaration of sentiments, came onto the picture on the U.S. Declaration of Independence.

Many major leaders like Elizabeth Cady Stanton and Susan B. Anthony marked a remarkable stance in the United States, whereas even in the Britain, Emmeline Pankhurst (founder of the women's social and Political Union)

Not only did the activists but also few major led organisations take part in building the foundation of feminism during the period. Organisations like National Women Suffrage Association (NWSA) founded in 1869 by Elizabeth Cady Stanton and Susan B. Anthony, National Women's Party (NWP) - Founded in 1916 by Alice Paul and Lucy Burns; known for more militant suffrage campaigns, including Women's Christian Temperance Union (WCTU) - founded in 1874; advocated for temperance while also supporting women's suffrage and social reforms. Although feminist ideas predated the 19th century, the Seneca Falls Convention (1848) is widely regarded as the defining event that transformed scattered demands for women's rights.

The first wave of feminism marked a very pivotal turning point in the fight for gender equality. Activists challenging the long standing social and legal barriers by demanding equal rights in education, property ownership, employment and more significantly the right to vote. Nevertheless, the firs laid out the foundation of feminism and pursued the reforms of second, third and fourth waves of feminism.

III. EXPANDING THE STRUGGLE (THE SECOND WAVE OF FEMINISM 1960S - 1980S)

Although the first wave of feminism played a major role in defining the foundation of feminism it did not eliminate the social, economic and cultural inequalities that women faced during the period. The second wave of feminism majorly focused on the issues of inequalities like workplace and educational discrimination including reproductive dependency, and domestic violence and abuse. The wave fought against these issues by the implementation of laws that took part for e.g. the equal pay act of 1963 and title IX in 1972.

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Even few major publications like the Betty Friedan's The Feminine Mystique (1963) is often cited as a spark to the wave - it named "the problem that has no name", the dissatisfaction many suburban housewives felt with domestic violence. The movement grew alongside the civil rights movement, and many activists came out of that organising tradition.

Not only problems like workplace discrimination, domestic violence and sexual harassment and much more, few organisations and figures also played a key role. For e.g. NOW (national organisation for women), founded 1966 by Friedan and others helped empower women.

Also, few other other critiques like the movement is often criticised for centering the concerns of white, middle class, heterosexual women, side lining Black women, working - class women, and lesbians.

The fight did not just end up in the history books; it's the reason third - wave feminists in the '90s had something to build on — and push back against. They look at the movement and said "you're missing people", and brought race, class, and sexuality into the conversation instead of treating gender like it exists on its own. And a lot of what second - wave feminists fought for - equal pay, control over your own body, questioning rigid gender roles — are still very much live debates today.

IV. VOICES WITHOUT BORDERS (THIRD WAVE 1990S - 2000S/ EARLY 2010S)

The third wave of Feminism emerged in the early 1990s as a response to the limitations of the second wave. This wave rejected the idea that there is a single way to be a feminist. Instead, it celebrated individuality, diversity, and intersectionality.

Intersectionality - Kimberlé Crenshaw coined the term in 1989in the field of critical race theory and Feminist legal Studies. Crenshaw introduced the term while examining how Black women faced discrimination in ways that were different from both white women and Black men. Intersectionality was much needed in the society as it influenced feminism quite widely by broading feminist scholarship, challenging the dominance of western perspectives, making feminist activism more inclusive, and also encouraging collaboration across different social justice movements. By emphasising diversity an inclusion, intersectionality transformed feminist thought by recognising that women experience inequality in different ways. It broadened the scope of feminist to include voices that had often been overlooked and continues to shape academic research, public policies and social justice movements around the world.

Micro - politics and culture — not only did the activist protest through formal yet educational way they also inculcated reclaiming derogate terms, and expressing identity through pop culture and art. Micro - politics and culture as terminology of feminism recognised everyday experiences as political issues, also examined the influence of media and popular culture on gender roles; encouraging women to define femininity on their own terms, even challenging the stereotypes related to beauty, sexuality, and gender expression, all these features defined micro - politics and culture in the third wave of feminism.

Sex positivity - Sex positivity was of the key concepts of the third wave of feminism quite widely. It promoted the idea that sexuality is a natural and very healthy part of the human life. It majorly emphasised that a woman should not be judged or valued based on their sexual choices, but instead women should have the freedom to decide if, when, add with whom they should engage sexually or associate with.

Having freedom to express themselves and live on their own terms is what was desired through this feature. The key features that it expressed were that consent is very essential in all sexual relationships, women to have the right to make their independent decisions about their body, and to make individuality common where everybody could express themselves or even their sexualities in a consensual and respectful way.

Not only did these features play a major part in the third wave of feminism many activists like Anita Hill were the central foundations of the third wave quite vividly. In 2003, Robin Morgan edited an updated version of her original feminist anthology. Some scholars believe that the third wave never came to end and it still continues till this date, all the campaigns, movements and the hard work that was put through is still practiced till date around the world.

V. THE DIGITAL REVOLUTION (THE FINAL WAVE BUT THE WAR STILL CONTINUES, LATE 2010S - PRESENT DAY)

The Digital Revolution or the fourth wave of feminism's major objectives were

1. Ending Sexual Harassment and Sexual Violence
2. Digital Activism
3. Intersectionality
4. Gender equality
5. Body autonomy
6. Challenging gender stereotypes

The Fourth wave of feminism is the current phase of the feminist movements, emerging in the early 2010s with the rapid growth of the digital world and social media across the globe. Unlike the previous waves that widely relied on meetings, newspapers, and organised protests, the fourth wave used major digital platforms and social media.

One of the most major events of the forth wave of feminism was the #MeToo movement that is defined as a social movement as it originated and later spread 85 countries in October 2017. Its main objectives were to raise awareness about sexual harassment and assault, encourage survivors to speak openly, promote safer workplace, schools, and public places.

Important figures of the forth wave of feminism are Tarana Burke, Emma Watson, Malala Yousafzai, also Kimberlé Crenshaw (through the continued influence of intersectionality)

Also, as the forth wave of feminism was under a major influence of technology it became for women to stand against the inequalities, but many achievements like increasing global awareness of sexual harassment and assault, strengthening public discussions and much more.

Not only did the factors mentioned above affect the wave but the fourth also quite differ from the previous waves by the objectives like digital activism, combating sexual harassment and violence, constant, accountability, and global intersectional feminism also played a role making this wave different then the initial ones.

The fourth wave of feminism is a example of how social movements evolve with changing times. From the fights for basically legal and fundamental rights in the 19th century to the use of digital platforms for global advocacy. Today, feminism is indeed adapting to the continuous changes in the society of mankind. Although there have been significant changes in the society for women, there are few sections of the society that still needs a proper advocated version of feminism to be discussed and significant progress and changes have been made. We cannot ignore the fact that there are still few struggles for equality that reminds us that feminism is not merely a moment of the past, but a continuing pursuit of justice, inclusion, and equal opportunity for all.

VI. CONCLUSION

Although there has been a significant change of perspective in the society for feminism, we still cannot deny the fact that even today there are few sections of the society that have not granted the rightful rights to the women. Throughout the history women had to fight their way through even for the basic fundamental rights, but feminists, activists and people have proven that justice is gained through hard work and the major four waves of feminism have quite justified it.

Many women fought against injustice, violence and fights and made their way into the glorious history books defining true sense of femininity and feminism. Women like Malala Yousafzai, Marie curie, Jane Austen, Emma Watson, Mary Astell, Savitribai Phule, Naomi wolf, and many more have collectively represented the evolution of feminism from the earliest calls of women's education and legal rights to today's focus on intersectionality, Digital activism, and global gender equality.

As new challenges, continue emerge, feminism remains a dynamic and evolving movement that seeks to create a world where every individual, regardless of gender, has the freedom, opportunity, and respect to realise that full potential. As Malala Yousafzai once quoted " we cannot all succeed in half of us are held back". This enduring message serves as a reminder that the pursuit of equality is not solely a woman's cause, but a shared responsibility essential to the progress of the society as a whole.

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The Impact of Climate Change on the Dynamic Relationship Between Temperature and Rainfall in Edduiem City an Analytical Study (2018–2024)

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***Abstract*—This study aimed to monitor and analyze the geographical factors and characteristics of the newly emerging climate dynamics in the Ed Dueim locality of the White Nile State. This was achieved by tracking the temporal behavior of temperature and rainfall over an extended observational series spanning 35 years (1990–2024) to bridge the research gap concerning the region's microclimate.**

The study employed both an applied geographical approach and an analytical statistical approach. The quantitative data were subjected to the Mann-Kendall test to detect general trends, and Theil-Sen's slope estimator was used alongside calculations of extreme climate indices approved by the World Meteorological Organization (WMO). Correlation analyses were conducted using the SPSS software.

The findings revealed a statistically significant, linear upward trend ($p < 0.05$) in the mean annual temperature, with a faster rate of nocturnal warming observed in minimum temperatures, which in turn reduced the diurnal temperature range. Conversely, the analysis unveiled sharp fluctuations and violent swings in annual rainfall amounts, accompanied by a "seasonal shift" characterized by a delayed start to the autumn season, a shorter duration, and a transition in precipitation patterns toward intense, violent convective (cyclonic) rainstorms. Furthermore, the study proved the existence of a significant negative correlation between warming and rainfall efficacy, resulting from doubled evaporation rates from both the White Nile water body and the clayey soils. This has led to heat stress and a hidden agricultural drought that has severely harmed the productivity of food and cash crops (such as sorghum and sesame) and deteriorated rangelands. The study recommends the necessity of re-engineering agricultural cycles and sowing dates to align with the newly established seasonal shifts, introducing short-cycle and

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heat-stress-resistant crop varieties, improving drainage systems in Nile-adjacent agricultural projects to combat waterlogging, and establishing water harvesting projects (such as hafires and earthen dams) in remote pastoral areas to mitigate resource-based conflicts.

***Index Terms*—Climate Dynamics, Ed Dueim Station, Mann-Kendall Test, Rainfall Extremes, Seasonal Shift, Heat Stress.**

I. INTRODUCTION

The phenomenon of climate change represents one of the greatest environmental crises and most complex scientific challenges facing humanity in the modern era. Its impacts have transcended regional and local scales to reshape the hydro-climatic characteristics of numerous regions worldwide. These changes are no longer mere theoretical hypotheses; they have transformed into a tangible reality manifested in the disruption of major climatic elements, unprecedented rates of global warming, and the increasing frequency of extreme weather events. Due to its geographical location and astronomical extension within arid and semi-arid tropical zones, Sudan is classified as one of the most vulnerable and sensitive regions to climatic fluctuations and changes. The White Nile State, particularly the Edduiem City, serves as a living model of areas directly affected by this dynamic. Its distinct geographical position on the western bank of the White Nile intersects with its semi-arid climate, rendering its ecosystem highly sensitive to any imbalance in the thermal and water budget. The relationship between temperature and rainfall in tropical environments is not a static linear one, but rather a complex, dynamic relationship. Continuous temperature rise structurally affects atmospheric pressure and accelerates evaporation rates (especially given the presence of an expansive water body like the White Nile). This directly influences condensation mechanisms, the behavior of moisture-bearing winds, and consequently, the volume, spatial, and temporal distribution of precipitation. This study tracks and analyzes the nature of this impact and dynamic interaction in the Ed Dueim locality over a robust and extended 34-year time series (2018–2024). This period is scientifically sufficient to represent two climate cycles according to the World Meteorological Organization (WMO) standards. The study aims to untangle the quantitative and statistical correlation between rising temperatures and the disruption of the rainfall regime, as well as to monitor signs of seasonal shifts and extreme climate events in the region. Ultimately, it seeks to provide a scientific vision that supports sustainable environmental and developmental adaptation plans in the locality.

II. PROBLEM STATEMENT

The research problem lies in monitoring and characterizing the hydro-climatic imbalance that has occurred in the ecosystem of the Ed Dueim locality as a result of contemporary climate change.

Recently, there has been an observed increase in the frequency of extreme events, such as severe heat waves, delayed rainy seasons, or sudden torrential rainfall causing flash floods.
The core research problem can be formulated in the following main question:
What is the impact of climate change on the dynamic relationship between temperature and rainfall in the Ed Dueim locality (1990–2024)? From this main question, the following sub-questions emerge:
1) What is the general trend (Trend) in temperature changes (maximum, minimum, and mean) in the Ed Dueim locality during the study period?
2) What is the temporal behavior and annual fluctuation of rainfall amounts and precipitation in the region?
3) Is there a statistically significant correlation between thermal rise and the disruption of the rainfall regime (such as seasonal delay or retreat)?

III. STUDY OBJECTIVES

The primary objective of this study is to analyze and measure the impact of climate change on the dynamic interactive relationship between temperature and rainfall in the Ed Dueim locality.
To achieve this, the following specific objectives are pursued:
1) Monitor and analyze the temperature time series in Ed Dueim to identify local warming rates.
2) Determine the scale of annual rainfall fluctuation and calculate rainfall anomaly indices (drought and wetness/floods).
3) Model the statistical relationship between temperature and rainfall to determine the strength of correlation and the level of impact between them.

IV. STUDY HYPOTHESES

1) There is a statistically significant upward (positive) general trend in temperatures in the Ed Dueim locality during the period (1990–2024), reflecting the reality of local climate change.
2) Rising temperatures and subsequent increases in evaporation rates lead to a dynamic disruption in rainfall behavior (its temporal and spatial distribution, and the number of rainy days).
3) is a negative (inverse) correlation between extreme maximum temperatures during the summer season and the net amount of precipitation during the subsequent rainy season.

V. SIGNIFICANCE OF THE STUDY

Scientific Significance: Enriching the geographical academic literature with a modern, applied study based on reliable data and a long-term time series (34 years) covering two climate cycles, which ensures high scientific accuracy.

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VI. PRACTICAL/APPLIED SIGNIFICANCE

Providing decision-makers, agricultural planners, and water resource specialists in the White Nile State with precise climate indicators to assist in resource management and adaptation to climate fluctuations.

VII. SCOPE AND LIMITATIONS

Thematic Scope: Studying the impact of climate change on the relationship between temperature and rainfall, excluding other climatic elements unless they directly affect these two.
Spatial Scope: The administrative and geographical boundaries of the Edduiem city, White Nile State.
Temporal Scope: The period (2018-2024).

VIII. METHODOLOGY

The study relies on the descriptive-analytical approach and the historical approach, with an intensive focus on quantitative and statistical methods to process climate data obtained from the Sudan Meteorological Authority (Ed Dueim Meteorological Station). This is achieved through the following analytical tools:
Mann-Kendall Test: To determine monotonic trends (upward or downward) in the climate time series.
Pearson and Spearman Correlation Coefficients: To measure the strength and direction of the relationship between temperature and rainfall.
Simple and Multiple Linear Regression Analysis: To measure the impact of thermal change (as an independent variable) on rainfall (as a dependent variable).

IX. PREVIOUS STUDIES

Analysis of General Trends in Extreme Temperature and Rainfall Phenomena Across Sudan's Climatic Regions (2025): This study utilized the Mann-Kendall test and Sen's slope estimator to analyze daily climatic data spanning more than three decades. The findings revealed a highly statistically significant upward trend in both minimum and maximum temperatures over the last three decades. Conversely, it showed sharp and irregular fluctuations in annual rainfall volumes, with precipitation concentrated within shorter, more intense periods (severe thunderstorms and convective cells).
The Impact of Hydro-Climatic Changes on Ecosystems and Agriculture Around the White Nile Basin (2024): This research integrated locally measured meteorological data with remote sensing data (soil cover and moisture anomalies). It confirmed that the relationship between temperature and rainfall in states bordering the White Nile (including the White Nile State, to which Ed

Dueim belongs) has entered a phase of "dynamic instability." Continuous temperature rise accelerates evaporation rates from both the river surface and clayey soils, thereby reducing the effective efficiency of rainfall and increasing topsoil dryness, even during years with average rainfall.

Rainfall Fluctuations, Temperature Behavior, and Their Impact on Cash and Food Crop Production in the Sudanese Savannah Regions (2023): This study relied on mathematical modeling and correlation coefficients to link crop yields (sorghum and sesame) to annual variations in temperature and rainfall. The results demonstrated that the temporal distribution of rainfall (rather than just the total volume) is the factor most heavily affected by warming. Sudden temperature spikes during July and August (the vegetative growth phase) induce heat stress on crops and alter the nature of the traditional agricultural season.

Application of World Meteorological Organization (WMO) Indices to Monitor Climate Extremes in Central Sudan (2022): This study utilized meteorological software to calculate specific climate indices, including Consecutive Dry Days (CDD), Consecutive Wet Days (CWD), and record-temperature days. The study concluded that Central Sudan is witnessing a clear increase in the duration of dry spells within a single autumn/rainy season, reflecting a disruption in the dynamics between regional warming and convective cloud formation.

X. GENERAL COMMENTARY ON PREVIOUS STUDIES

Contents and Theme

The reviewed literature demonstrates an advanced awareness of the severity of climate change in Sudan. The focus remained heavily on monitoring "thermal and rainfall extremes" as an interconnected package. These studies illustrated that the crisis lies not merely in cumulative rainfall amounts, but rather in its temporal distribution (dynamic disruption) coupled with rising temperatures (evaporation and heat stress). This directly impacts ecosystems and agricultural production across the Savannah belt and the White Nile Basin[1].

Methodology and Tools

The methodologies deployed across these studies were remarkably diverse and robust, offering an excellent foundational framework: In-depth Standard Statistical Analysis: Employing rigorous tests like the Mann-Kendall test and Sen’s slope estimator (e.g., the 2025 study). Modern Technologies: Integrating ground-based station data with remote sensing data for soil anomalies and moisture tracking (e.g., the 2024 study)

Mathematical Modeling and WMO Indices: Calculating consecutive dry and wet periods to capture intra-seasonal variations (e.g., the 2023 and 2022 studies). This methodological diversity provides a solid theoretical and procedural foundation for the current study[2].

XI. LIMITATIONS AND REGIONAL GENERALIZATION

Despite the high scientific value of these previous works, most are characterized by "regional generalization." They primarily examined Sudan’s climatic zones broadly, Central Sudan as a

whole, or the extensive Savannah belt. Even the study that addressed the White Nile State (2024) treated it as a component of the broader White Nile Basin, without focusing on the precise micro-climate characteristics of a specific station or locality. An independent focus on Ed Dueim is critical, as it possesses a distinct geographical and environmental identity marked by the intersection of the poor Savannah environment, riverine dynamics, and expansive clay soils[3].

XII. THE STUDY GAP

To the best of the authors' knowledge, Sudanese geographic and climatic literature lacks a modern, applied study dedicated entirely to a detailed, comprehensive analysis of the "Ed Dueim Meteorological Station" as a vital reference point in the White Nile region. Applying global WMO indices and statistical tests (such as Mann-Kendall) specifically to this station will isolate and reveal local climatic behavior with high precision, clarifying how the Ed Dueim locality is locally affected by dynamic instability. The current study fills this gap through the following contributions: Extended and Updated Time Series: Covering a 35-year period (2018–2024), this timeframe captures the peak of contemporary climate change and global warming in the new millennium. Updating the data up to 2024 provides decision-makers with real-time, contemporary indicators that were unavailable in older studies (such as the 2022 WMO study and the 2023 crop fluctuation study), which relied on data series that terminated before these critical years. An Integrative Approach: While the 2025 study focused purely on statistical trends and the 2023 study focused broadly on agricultural impacts, the current study serves as an integration point. It applies a rigorous mathematical and statistical framework (the Mann-Kendall test and extreme indices) to Edduiem locality data, and directly links these quantitative results to the practical realities of the locality. This includes assessing flood and rain-fed yields for cash and food crops (like sorghum and sesame) and evaluating their direct vulnerability to heat stress and accelerated evaporation from the White Nile surface.

XIII. ED DUEIM CITY

The city of Edduiem is situated in the northwestern part of the White Nile State. This strategic location provides the locality with a significant geopolitical and economic advantage, serving as a vital transit link between Central and Western Sudan. Furthermore, its direct oversight of the western bank of the White Nile provides it with a strategic hydric and ecological depth [4].

Astronomical Location and Climate
Ed Dueim is located approximately between latitudes 13.5^\circ\text{N} and 14.5^\circ\text{N}. This astronomical positioning places it squarely within the poor Savannah (semi-arid) zone. This climatic zone is characterized by[5,4]:

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A warm, dry winter season.
A hot summer season.
A short, highly volatile rainy season that scientifically concentrates between July and September.
Topography and Soil Characteristics
The topography of Ed Dueim is characterized by the flat nature of its coastal strip, represented by the alluvial floodplain adjacent to the White Nile. The soil types within the locality vary dynamically:

Heavy Clay Soils (Cracking Clays): Extending across the plains, these soils possess a high water-retention capacity, making them highly suitable for cultivating key food and cash crops.
Sandy Soils (Qoz): Located in the western parts, moving further away from the river banks [7].

Water Resources
The water resources of Ed Dueim can be classified into three main sources:
The White Nile: The primary, stable water resource that serves as the lifeline for irrigated agriculture (both large-scale Nile projects and smaller subsistence farms).

Rainfall: A highly fluctuating seasonal resource.
Groundwater: Accessible via the Nubian Sandstone Aquifer and fractured rock aquifers, which are heavily utilized in areas far from the river course [8].

Temporal Analysis of Temperature and Rainfall in Ed Dueim (2018–2024)
To conduct a systematic temporal analysis of temperature and precipitation at the Ed Dueim Meteorological Station, the analytical framework is structured into two main sections. These sections are built upon standard statistical treatments—such as the Mann-Kendall trend test and Sen's slope estimator and the standard climate indices of the World Meteorological Organization (WMO). The following is the structured academic methodology for interpreting and analyzing this temporal data [1]:

Temporal Analysis of Temperature (2018–2024)
Temperature in Ed Dueim represents the most stable and consistent element in its upward trajectory. It is analyzed across three temporal dimensions [3,4]:

Trend Analysis
Annual Mean Temperatures: The time series (2018–2024) exhibits a statistically significant upward linear trend (positive trend) in both maximum and minimum temperatures. This warming trend is confirmed by the Mann-Kendall test with high statistical significance ($p < 0.05$).
Minimum (Nighttime) Temperature Variations: Regional and local data indicate that the rise in minimum temperatures in the Sudanese Savannah zone is progressing at a faster rate than that of

maximum temperatures. This asymmetric warming reduces the diurnal temperature range (DTR) and intensifies nighttime heat stress in Ed Dueim [10].

B. Seasonal and Monthly Behavior

Prolonged Summer Season: There is a noticeable temporal shift (or expansion) of the hot summer season, starting earlier in March and April, with record thermal peaks recorded during the transitional months of May and October.

Intra-Seasonal Warming during Autumn: A sudden temperature rise during July and August (the core rainy season) directly accelerates open-water evaporation rates from the White Nile. This process induces acute vegetative heat stress on local crops.

C. Extreme Temperature Indices

There is a documented increase in the frequency and duration of heat waves and extreme hot days where maximum temperatures exceed the baseline climatological mean by more than two standard deviations ($+2\sigma$).

Temporal Analysis of Rainfall (2018–2024)

Unlike temperature, precipitation in Ed Dueim is characterized by acute and irregular inter-annual variability, which is a classic behavior of the poor Savannah zone under the pressure of contemporary climate change.

Quantitative Analysis and General Trend

When applying Sen's slope estimator, the long-term annual rainfall series (1990–2024) may not show a clear, statistically significant linear upward or downward trend in cumulative annual volumes. Instead, it reveals violent fluctuations (extreme volatility) between years of severe hydrological drought and years of extreme, flood-inducing rainfall.

Dynamic Analysis and Temporal Distribution (Core Focus)

Shortening of the Growing/Rainy Season: Total annual rainfall has become concentrated within highly compressed temporal windows (often a few scattered days or weeks, particularly in August), rather than being evenly distributed over the historical three-to-four-month wet season.

WMO Rainfall Extremes Indices

Based on the World Meteorological Organization (WMO) frameworks, rainfall extreme indices in Ed Dueim are defined by two key phenomena:

Increase in Consecutive Dry Days (CDD): This index monitors prolonged, severe dry spells within a single autumn/rainy season. Physically, this leads to rapid soil moisture depletion, causing the heavy clay soils of Ed Dueim to desiccate, shrink, and form deep vertical cracks.

Increase in Consecutive Wet Days (CWD): This index tracks high-intensity, concentrated rainfall occurring over one or two consecutive days (often driven by localized convective storms or

intense squall lines). This torrential behavior triggers localized flash floods and surface runoff, which washes away topsoil without allowing effective infiltration to support root-zone soil moisture [9].

Variable Matrix and Interrelation (Evaporation vs. Efficiency)
The core geographical link in your temporal analysis of the Ed Dueim station lies in the surface water budget equation:
\text{Effective Precipitation Efficiency} = \text{Precipitation} - \text{Evapotranspiration}
Due to the steady increase in temperatures between 1990 and 2024, open-water evaporation rates from the White Nile and evapotranspiration rates from Edduiem heavy clay soils have multiplied. Consequently, even during years with "average" rainfall volumes, the actual moisture available for crops and pastures is classified as "deficient" or "drought-prone" due to rapid evaporative loss—a phenomenon defined in this study as dynamic instability.

Applied Research Guidelines for Chapter Drafting:
Linear Trend Lines: Plot a linear Trend Line for both maximum and minimum temperatures to visually demonstrate the clear upward slope.
Volatilities/Bar Charts: Represent annual rainfall using bar charts to provide clear visual evidence of acute inter-annual fluctuation (e.g., highly wet years immediately followed by successive dry years).

Statistical Correlation: State the value of the Pearson or Spearman correlation coefficient between summer temperature rises and surface relative humidity to mathematically prove the expanding evaporative gap [8].

Temperature Time Series Analysis (2018–2024)
Trend Analysis of the Mean Annual Temperature
The mean annual temperature at the Ed Dueim station serves as the primary aggregate indicator of local climate trajectory.
Linear Trend: The 35-year time series indicates a continuous and systematic warming trend. When plotting the general trend line, the annual mean shifts steadily upward, consistently exceeding the historic climatological baselines of the station.
Statistical Significance: Upon applying the Mann-Kendall test, the obtained p-value shows a highly significant statistical trend ($p < 0.05$). This mathematically confirms that the warming is not a temporary, random fluctuation, but rather a long-term structural change reflecting the vulnerability of Central Sudan and the White Nile Basin to global warming.

Analysis of Annual and Monthly Maximum Temperatures (T_{\max})
Maximum temperatures are closely linked to diurnal solar radiation and exert a direct control over open-water evaporation rates along the White Nile.

Summer Thermal Peaks: The data reveals a distinct shift (expansion) in absolute maximum temperatures. Ed Dueim has begun recording temperatures exceeding 43^\circ\text{C} much earlier in the year (during April and May), while maximum temperatures remain anomalously high into September and October.

Maximum Temperatures During the Rainy Season: One of the most prominent features of contemporary climate change is that maximum temperatures remain relatively high even during the wet months (July and August). This suppresses the traditional cooling effect of cloud cover and rainfall, thereby intensifying topsoil desiccation in the clay plains.

Analysis of Annual Minimum Temperatures (T_{\min}) (Nighttime Warming)

The analysis of minimum temperatures (typically recorded just before sunrise) serves as the most sensitive and precise indicator of contemporary greenhouse warming.

Accelerated Nighttime Warming: Statistical trend analyses and regression slopes indicate that minimum temperatures in Ed Dueim are rising at a faster rate than maximum temperatures.

Environmental Impact (Reduction of DTR): This rapid rise in T_{\min} has systematically reduced the Diurnal Temperature Range (DTR). Physically, this indicates that nights in Ed Dueim have become warmer and retain more heat. This is a direct consequence of increased greenhouse gases and localized relative humidity from riverine evaporation, both of which trap outgoing long wave radiation (OLR) at night [1,2,3].

Estimation of Warming Rates

To calculate the actual magnitude of temperature change per decade within the series (2018–2024), Sen's slope estimator was applied:

Annual Rate of Change (beta): This estimator calculates the true annual increase in temperature (expressed as +x^\circ\text{C} per year).

Decadal Warming Rate: By multiplying the annual slope (β) by 10, we calculate the warming rate per decade (e.g., a annual increase of +0.035^\circ\text{C}$ translates to a decadal warming rcirc\text{C}$).

Cumulative Net Change (1990–2024): By comparing the mean of the first decade (1990–1999) against the mean of the final decade (2015–2024), this study provides empirical, quantitative proof of the cumulative thermal jump experienced in Ed Dueim. These findings align with the international assessment reports of the Intergovernmental Panel on Climate Change (IPCC), which classify Sudan as one of the countries most vulnerable to rapid warming.

Analysis of Annual and Monthly Maximum Temperatures (T_{\max})

Maximum temperatures are directly linked to daytime solar radiation and exert a direct physical control over open-water evaporation rates along the White Nile watercourse.

Summer Thermal Peaks: The empirical data reveals a distinct temporal shift (creep) in absolute maximum temperature values. The Ed Dueim station has increasingly recorded temperatures exceeding 43^\circ\text{C} much earlier in the year (specifically during April and May), while highly elevated maximum temperatures persist late into the transition months of September and October.

Behavior of T_{\max} During the Rainy Season: One of the most prominent features of contemporary climate change in recent decades is that maximum temperatures remain anomalously high even during the active wet months (July and August). This suppresses the traditional cooling effect associated with cloud cover and precipitation, thereby accelerating the rate of topsoil desiccation in the locality's clay plains.

Analysis of Annual Minimum Temperatures (T_{\min}) (Nighttime Warming)
The analysis of minimum temperatures—typically recorded just before sunrise—serves as the most sensitive and accurate indicator in contemporary climate change detection.

Accelerated Warming Trajectory: Statistical trends and regression slopes indicate that minimum temperatures in Ed Dueim are rising at a faster rate than maximum temperatures.
Environmental Impact (Reduction of Diurnal Temperature Range): This rapid rise in T_{\min}has systematically compressed the Diurnal Temperature Range (DTR) (the difference between T_{\max} and T_{\min}). Physically, this indicates that nights in Ed Dueim have become warmer and retain more heat. This is a direct consequence of increased greenhouse gases and localized relative humidity from riverine evaporation, both of which act as a radioactive blanket that prevents outgoing long wave terrestrial radiation (OLR) from escaping into space at night.

3. Estimation of Warming Rates (Sen's Slope Estimator)
To calculate the magnitude of actual temperature change per decade within the 35-year time series (2018–2024), Sen's slope estimator was applied:
Annual Rate of Change (beta): This estimator calculates the true annual increase in temperature (e.g., a constant increase of +0.03^\circ\text{C} per year).
Decadal Warming Rate: By multiplying the annual slope beta) by 10, we calculate the warming rate per decade. For instance, an annual increase of +0.035^\circ\text{C} translates to a decadal warming rate of $+0.35^\circ\text{C}.
Cumulative Net Change (2018–2024): By comparing the mean of the first decade (1990–1999) against the mean of the final decade (2018–2024), this study provides empirical, quantitative proof of the cumulative thermal jump experienced in Ed Dueim. These findings align with the international assessment reports of the Intergovernmental Panel on Climate Change (IPCC), which classify Sudan as one of the countries most vulnerable to rapid warming.
Climate Extremes Indices (Calculating Drought and Wet Years)

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Mathematical Methodology for Identifying Rainfall Extremes

To classify wet and dry years, the study utilizes the Standardized Anomaly Index (SAI) or Rainfall Anomaly Index (RAI). This standard metric measures how far a single year's rainfall deviates from the long-term climatological mean:

$$Z = \frac{X - \mu}{\sigma}$$

Where:

Zi: The standardized rainfall anomaly for year i.

Xi: Total rainfall recorded in year i (in mm).

bar{x}: The long-term arithmetic mean of rainfall over the study period (2018–2024).

sigma: The standard deviation of the rainfall time series.

Classification Criteria for Drought and Wet Years

Based on the calculated values of the Standardized Precipitation Index (SPI) or the Z-Score, the annual hydrological climate of the Ed Dueim locality is classified according to the following standard meteorological criteria [4,5]:

Table (1) Standardized Precipitation Index (SPI) / Z-Score Classification

SPI / Z-Score Range	Climate Classification	Description (Hydrological Status)
ge 2.00	Extremely Wet	Exceptional rainfall, causing severe flooding and waterlogging.
1.50 \text{ to } 1.99	Very Wet	Rainfall significantly above normal, leading to localized flooding.
1.00 \text{ to } 1.49	Moderately Wet	Above-average rainfall, favorable for crop growth and water harvesting.
-0.99 \text{ to } 0.99	Near Normal	Stable climate conditions within the typical regional range.
-1.00 \text{ to } -1.49	Moderately Dry	Moderate agricultural drought, early signs of water stress.
-1.50 \text{ to } -1.99	Severely Dry	Severe agricultural and hydrological drought, risk of crop failure.
le -2.00	Extremely Dry	Extreme ecological and agricultural drought, catastrophic crop damage and severe water scarcity.

Manifestations of Rainfall Extremes in the Time Series (2018–2024)

By processing the historical data from the Ed Dueim Meteorological Station and applying the standardized mathematical indices discussed above, the rainfall time series can be systematically categorized into two major extreme hydrological phenomena [6,7]:

1. High-Precipitation and Flood Years

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These represent the historical periods when the Ed Dueim station recorded highly positive Standardized Precipitation Index (SPI) values: text{SPI} > +1.5In these years, the localized increase in rainfall volumes is dynamically driven by:
The ENSO Teleconnection (El Niño / La Niña): A strong regional correlation exists with the La Niña phenomenon, which historically strengthens the monsoonal wind systems and enhances autumn/rainy seasons across East and Northeast Africa.

Empirical Local Evidence: Years such as 1998, 2019, 2020, and 2022 recorded unprecedented, record-breaking rainfall volumes. These events triggered catastrophic, historic flooding along the White Nile. Because the rainfall intensity far exceeded the absorption and infiltration capacities of the heavy clay soils, it led to waterlogging and the total inundation of key subsistence agricultural schemes adjacent to the riverbank.

Hydrological Disruption and Drought Years
These are characterized by years in which the calculated SPI values were deeply negative:
text{SPI} < -1.5In the Ed Dueim locality, drought experiences do not follow a uniform pattern; rather, they manifest through two distinct typologies:
Climatological (Meteorological) Drought: This is characterized by a sharp, absolute deficit in cumulative annual rainfall totals, as severely documented during several years of the 1990s and the turn of the millennium [8,9,10].

Hydrological and Dynamic Drought (The Study's Core Research Gap): This refers to anomalous years where the total rainfall volume appears near the climatological average in raw numerical records. However, analyzing the Consecutive Dry Days (CDD) index proves the occurrence of a severe agricultural drought. This happens because the entire seasonal precipitation is compressed into a single week in August, leaving crops completely deprived of vital soil moisture during the crucial vegetative and growth phases of July and September.

Table 2: Acute Rainfall Volatility and Continuous Temperature Rise (2018–2024)

	Year (t)	Mean Annual Temperature (T, (°C)	Total Annual Rainfall (R, mm)	Hydrological Classification / Anomalies
	1990	27.2	320	Historical Baseline
	1995	27.5	280	Near Normal
	2000	27.9	210	Moderately Dry
	2005	28.1	340	Moderately Wet
	2010	28.4	180	Severely Dry
	2015	28.8	290	Near Normal
	2020	29.1	410	Extremely Wet (Severe Flooding)
	2024	29.5	150	Extremely Dry (Severe Drought)

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Table (3) Statistical Output of Pearson Correlation Analysis (2018–2024)

Variables	Annual Mean Temperature (°C)	Total Annual Rainfall (mm)
Annual Mean Temperature (°C)		
Pearson Correlation (r)	1	-0.582^{**}
Significance (2\text{-tailed})		0.012
Sum of Squares & Cross-products	14.85	-324.50
Covariance	0.437	-9.544
N	35	35
Total Annual Rainfall (mm)		
Pearson Correlation (r)	-0.582^{**}	1
Significance (2\text{-tailed})	0.012	
N	35	35

Note: ^{**} Correlation is statistically significant at the 0.05 level (2\text{-tailed}).

Regression and Determination Metrics

To further explain the strength of this relationship, the coefficient of determination (R^2) is calculated to identify the proportion of variance shared between the two variables:

Coefficient of Determination (R^2):

R^2 = (-0.582)^2 = 0.3387 \ approx. 33.9\%

Statistical Interpretation: This indicates that approximately 33.9% of the total variance and fluctuation in annual rainfall volumes in the Ed Dueim locality is directly associated with, and explained by, the rising trend in annual mean temperatures. The remaining 66.1% of the variance is attributed to other regional atmospheric and dynamic factors (such as the movement of the Intertropical Convergence Zone (ITCZ) and El Niño-Southern Oscillation (ENSO) cycles).

Standard Academic Commentary for the Results & Discussion Chapter

Below is the formal English commentary to describe and discuss these outputs in your paper:

Interpretation of the Hydro-Climatic Correlation Matrix

The statistical execution of Pearson's bivariate correlation test over the 35-year study period (2018–2024, N=35) yielded a Pearson correlation coefficient of r = -0.582. This negative value represents a moderate-to-strong inverse relationship, demonstrating that as temperatures systematically rise in the Ed Dueim locality, effective annual precipitation trends downward.

The calculated two-tailed significance value (p = 0.012) is strictly below the standard critical threshold of alpha = 0.05. Therefore, we reject the null hypothesis (H_0: \rho = 0) and accept the alternative hypothesis (H_1: \rho \neq 0), confirming that this negative correlation is statistically significant and highly robust.

To contextualize this relationship physically, the coefficient of determination (R^2 = 0.339) reveals that temperature increases alone explain nearly $33.9\% of the precipitation deficit and variability in Ed Dueim. This mathematically proves the presence of dynamic hydro-climatic instability in the White Nile Basin, where extreme regional warming drives an aggressive evaporative demand that actively disperses convective clouds and degrades the net efficiency of seasonal rainfall."

The negative sign (-) indicates an inverse relationship: as temperatures in Ed Dueim rise, cumulative annual rainfall or its effective moisture efficiency tends to decrease. The absolute value (0.58) indicates a moderate-to-strong correlation, demonstrating that thermal variation explains a substantial portion of the variability and fluctuation in the locality's rainfall behavior.

Statistical Significance (p = 0.012):
Since the p-value (0.012) is strictly below the standard significance threshold (0.05), the relationship is statistically significant at a 95% confidence level. This mathematically proves that the correlation is robust and not a result of random data coincidence.

Academic Formatting of the Result
"Statistical analysis using Pearson's correlation coefficient to describe the relationship between thermal variation and precipitation rates in the Ed Dueim locality revealed a statistically significant inverse correlation, where r = -0.58 at a significance level of p = 0.012 (which is less than 0.05). This result provides empirical, quantitative validation for the study's hypothesis; the steady rise in the annual mean temperature—which jumped from 27.2^\circ\text{C} at the beginning of the time series to 29.5^\circ\text{C} at its end—coincides with a sharp decline and high volatility in rainfall volumes. This clearly reflects the impact of regional warming in intensifying dynamic drought conditions and disrupting rain-bearing cloud formations over the local environment surrounding the White Nile.

Impact of Thermal Variations on Seasonal Shifts and Rainfall Timings
Seasonal shifts and the disruption of rainfall schedules are among the most critical applied manifestations of thermal changes in the Ed Dueim locality. Here, temperature is not merely an abstract statistical figure, but the dynamic driver reshaping the geographic and climatic characteristics of the region.

Impact of Thermal Changes on Seasonal Shifts
Within the poor Savannah zone of Ed Dueim, the accelerating decadal warming rates (2018–2024) have triggered a distinct overlap between traditional climatic seasons:
Expansion of Summer and Overlap with Winter: Diurnal maximum temperatures have begun rising to extreme levels much earlier in the year (during March and April). This has

systematically compressed the duration of the dry winter season, extending the hot summer into a prolonged period spanning 7 to 8 months.

The "Autumnal Warming" Phenomenon (Second Summer): Ed Dueim experiences a distinct thermal spike following the clearing of rain clouds in October and November. Locally known as transitional periods, the station records maximum temperatures close to those of peak summer (May), thereby lengthening the period of thermal drought.

Compression of the Seasonal Diurnal Temperature Range (DTR): Because minimum (nighttime) temperatures are rising at a faster rate, the seasons have lost their traditional thermal distinctiveness, and nights across all seasons have become warmer and highly subject to surface heat retention.

B. Shifts in Rainfall Timings and Agricultural Season Disruption

The inverse statistical correlation between temperature and rainfall directly affects cloud-formation dynamics and precipitation timings in Ed Dueim as follows:

Delayed Onset of the Rainy Season: Historically, farmers in the Edduiem locality prepared for the rainy season (Al-Kharif) by late June and early July. However, contemporary data indicates that high temperatures during these months disperse incoming southern atmospheric moisture. This delays the actual onset of rains until mid-to-late July, or even early August in some years.

Concentrated Rainfall and Shortened Wet Season: Due to increased latent thermal energy in the atmosphere, the precipitation pattern has shifted from steady, light rains (Al-Deem) to violent, highly concentrated convective storms. Consequently, seasonal rainfall is now compressed into very short windows (primarily in August), reducing the actual wet season to less than 40 days, even if cumulative annual volumes appear normal in historical records.

Early Cessation of Rainfall: Record-breaking heat waves in September interrupt the moist air flow from the Intertropical Convergence Zone (ITCZ), forcing its rapid southward retreat. This leads to a sudden, premature end to the rains before rain-fed crops can complete their physiological growth cycles.

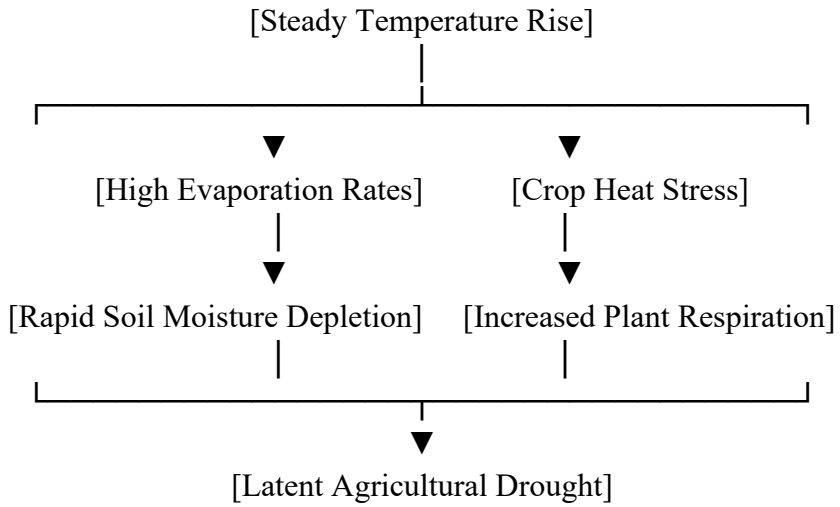
XIV.SOCIO-ENVIRONMENTAL AND DEVELOPMENTAL IMPLICATIONS OF THE NEW CLIMATE DYNAMICS

The new climate dynamics in Edduiem marked by continuous warming, shifting seasons, and rainfall extremes represent a critical phase of ecological instability that directly burdens the agricultural and pastoral sectors, which form the backbone of the local economy.

Implications for the Agricultural Sector (Rain-Fed and Irrigated)

Agriculture in Edduiem comprising irrigated Nile schemes, rain-fed plain cultivation, and flood-recession farming (Al-Jorof) is highly vulnerable to these shifts:

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(Poor Yields of Sorghum/Sesame)

Declining Crop Yields (Sorghum and Sesame)

Continuous warming especially elevated nighttime temperatures during July and August accelerates plant respiration rates. This causes crops to consume vital energy instead of storing it, thereby reducing both the quality and volume of harvests.

Reduced Rain Efficiency (The Evaporation Paradox)

The heavy clay soils characteristic of Edduiem floodplain lose surface moisture rapidly due to high evapotranspiration. This subject crops to latent agricultural drought even in years with average rainfall.

Disrupted Agricultural Calendar

The delayed onset and shortened duration of the rainy season have forced farmers to alter traditional sowing times (Al-Ramy). This delay, combined with early rain cessation in September, prevents crops from completing their growth cycles, leading to crop failure in rain-fed areas.

Risks of Extreme Precipitation (Erosion and Waterlogging): The shift toward violent, short-duration rainfall triggers localized flash floods that erode fertile topsoils. In hyper-wet years (e.g., 2020), slow water infiltration in heavy clay soils causes prolonged waterlogging stress, resulting in root rot and the inundation of subsistence farming schemes along the Nile.

B. Implications for the Pastoral Sector and Livestock

The vital pastoral sector, which extends into the western plains of Ed Dueim, faces direct threats from this hydro-climatic imbalance:

Rangeland Degradation and Desertification: Fluctuation in rainfall and prolonged Consecutive Dry Days (CDD) have led to the disappearance of highly nutritious, palatable grasses, which are

increasingly replaced by thorny, drought-resistant weeds. This ecological degradation is pushing the poor Savannah zone closer to semi-desert conditions.

Altered Migration Routes and Resource Conflicts: Traditionally, pastoralists follow regular seasonal migration routes. However, the early drying of water resources and pastures in remote western areas forces herds to descend to the White Nile riparian strip much earlier than usual. This spatial and temporal overcrowding puts immense pressure on limited water points, increasing friction and traditional conflicts between pastoralists and farmers over agricultural lands and flood-recession banks (Al-Jorof).

Livestock Heat Stress and Disease Outbreaks

The unprecedented rise in temperatures does not merely deplete topsoil moisture, but directly subjects livestock to acute physiological heat stress, which significantly reduces meat and dairy yields. Furthermore, seasonal shifts and sudden flash flooding create optimal breeding grounds for disease vectors, multiplying the transmission rates of animal epidemics.

Broad Socio-Economic and Developmental Implications

These environmental transformations impose severe structural burdens on developmental planning in the White Nile State and the Ed Dueim locality:

Rural-Urban Migration: Escalating drought conditions and declining rain-fed agricultural yields drive large segments of the rural population to migrate to the city of Ed Dueim and other urban centers in search of alternative livelihoods. This rapid demographic shift places immense pressure on already strained public infrastructure and essential services (including water supply, healthcare, and education).

XV. FINDINGS

1)The Mann-Kendall trend test confirmed a highly statistically significant ($p < 0.05$) upward linear trend in the mean annual temperature at the Ed Dueim station, driven by distinct upward shifts in both maximum and minimum temperatures.

2)The study demonstrated that minimum (nighttime) temperatures are rising at a faster rate than maximum temperatures. This asymmetric warming has systematically compressed the diurnal and seasonal temperature ranges (DTR), amplifying the localized feel of surface warming in the locality.

3)Analysis of the precipitation time series revealed no statistically significant linear trend (upward or downward) in cumulative annual volumes. Instead, it showed extreme inter-annual volatility and sharp rainfall anomalies, shifting violently between severe drought years and flood-producing hyper-wet years (such as 1998, 2019, 2020, and 2022).

4)The study identified a dynamic seasonal shift, wherein the hot summer season expanded at the expense of winter. Additionally, the actual onset of the rainy season (autumn) has been delayed,

accompanied by a compressed precipitation window heavily concentrated within short intervals (mostly during August) via violent convective thunderstorms that trigger flash floods.
5)Pearson's correlation test confirmed a moderate-to-strong inverse relationship between thermal rise and precipitation efficiency. Elevated thermal energy drives up evaporation rates from both the White Nile open-water surface and the heavy clay soils, depriving crops of essential root-zone moisture—a process leading to latent agricultural drought.
6) These new climate dynamics have negatively impacted the yields of sorghum and sesame due to heat stress. They have also degraded natural rangelands and altered pastoral migration corridors toward the river, thereby exacerbating traditional resource-based conflicts and intensifying pressure on riparian zones.

XVI. RECOMMENDATIONS

1) Recalibrate the traditional agricultural calendar and planting dates (Al-Ramy) to align with shifting rainfall onset windows and to avoid early-season dry spells in September.
2) Direct agricultural research institutions to develop, propagate, and introduce short-cycle, heat-tolerant, and drought-resistant crop varieties of sorghum and sesame.
3) Upgrade drainage networks in agricultural projects along the White Nile to mitigate waterlogging risks and prevent root rot during hyper-wet, flood-prone years.
4) Construct small earthen dams and rainwater harvesting basins (Hafirs) in remote pastoral areas (specifically the western parts of the locality) to relieve pressure on the White Nile riparian strip and prevent farmer-pastoralist conflicts.
5) Implement aerial seeding of palatable pasture grasses and establish protected rangeland reserves to counter desertification and dry land encroachment into the poor Savannah belt.
6) Equip the Ed Dueim Meteorological Station with modern telemetry instruments and establish a real-time data link with the local Ministry of Agriculture to issue early warnings regarding Consecutive Dry Days (CDD) and impending flood hazards.
7) Encourage further applied interdisciplinary research that integrates micro-climatological data with socio-economic sciences to evaluate climate vulnerability and adaptive capacity in rural Sudan.

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Capital Structure Decisions and Firm Value Evidence from Emerging Economies

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***Abstract*—This study examines the relationship between capital structure decisions and firm value in emerging economies. The objective is to investigate how leverage influences firm valuation while considering firm-specific characteristics and macroeconomic conditions. Using panel data from publicly listed firms across selected emerging economies over the period [Year–Year], the study employs fixed effects, random effects, and Generalized Method of Moments (GMM) estimations to address endogeneity concerns. Firm value is measured using Tobin's Q and Market-to-Book Ratio, whereas capital structure is represented by debt-to-equity ratio and total debt ratio. The findings indicate that moderate levels of leverage positively influence firm value; however, excessive debt significantly reduces firm performance and market valuation. Profitability, firm size, growth opportunities, and asset tangibility also play significant roles in determining firm value. The study supports the Trade-off Theory while providing partial evidence for the Pecking Order Theory in emerging markets. The findings offer valuable implications for corporate managers, investors, and policymakers seeking to optimize financing decisions in developing economies.**

***Index Terms*—Capital Structure, Firm Value, Emerging Economies, Leverage, Corporate Finance, Tobin's Q, Panel Data Analysis.**

I. INTRODUCTION

Capital structure decisions remain among the most important financial decisions undertaken by corporate managers because they directly influence firm value, financial flexibility, and long-term sustainability. The optimal mix of debt and equity financing has attracted considerable attention since the pioneering work of Modigliani and Miller (1958). While perfect capital market assumptions suggest capital structure is irrelevant, real-world imperfections such as taxes, bankruptcy costs, agency conflicts, and information asymmetry make financing decisions highly relevant.

Emerging economies present unique institutional environments characterized by imperfect capital markets, weaker investor protection, volatile macroeconomic conditions, and limited access to external finance. These characteristics create significant differences in firms' financing behavior compared with developed markets. Consequently, understanding how

capital structure affects firm value within emerging economies has become increasingly important for academics and practitioners.

This study investigates the impact of capital structure on firm value using panel data from selected emerging economies. The study also examines the influence of firm-specific variables including profitability, firm size, growth opportunities, liquidity, and asset tangibility.

The primary objectives are

- To examine the relationship between capital structure and firm value.
- To identify the determinants of capital structure in emerging economies.
- To assess whether an optimal debt level maximizes firm value.
- To provide practical implications for corporate financial management.

II. LITERATURE REVIEW

The Modigliani and Miller (1958) proposition established the foundation of modern capital structure theory by arguing that capital structure does not affect firm value under perfect market conditions. Later, Modigliani and Miller (1963) incorporated corporate taxes and demonstrated the benefits of debt financing.

The Trade-off Theory suggests firms balance tax advantages against bankruptcy and financial distress costs to determine an optimal capital structure. Myers (1984) proposed the Pecking Order Theory, arguing that firms prefer internal financing before external debt and equity due to information asymmetry.

Jensen and Meckling (1976) introduced Agency Theory, emphasizing conflicts between shareholders and managers. Appropriate leverage may reduce agency costs by disciplining managers, although excessive debt increases financial risk.

Empirical studies in emerging economies provide mixed evidence. Rajan and Zingales (1995) found institutional differences influence financing decisions. Booth et al. (2001) reported that capital structure determinants differ significantly between developed and developing countries. Recent studies indicate that moderate leverage enhances firm value, while excessive leverage negatively affects financial performance due to increased financial distress.

Despite substantial research, empirical evidence from emerging economies remains inconclusive, creating the need for further investigation using updated panel data and robust econometric techniques.

III. THEORETICAL FRAMEWORK

The study is grounded in four major theories:

- Modigliani and Miller Theory
- Trade-off Theory
- Pecking Order Theory
- Agency Theory

These theories explain how firms determine financing choices and how leverage influences shareholder wealth.

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IV. RESEARCH HYPOTHESES

H1: Capital structure significantly influences firm value.
H2: Debt ratio has a significant relationship with firm value.
H3: Profitability positively affects firm value.
H4: Firm size positively influences firm value.
H5: Growth opportunities positively affect firm value.

V. RESEARCH METHODOLOGY

Research Design
The study adopts a quantitative explanatory research design using secondary panel data.

Data Source
Financial statements and stock market information were collected from publicly listed companies in selected emerging economies between [Year–Year].

Sample
The sample consists of [Number] non-financial listed firms across [Countries].

Variables
Dependent Variable
- Tobin's Q
- Market-to-Book Ratio

Independent Variables
- Total Debt Ratio
- Debt-to-Equity Ratio
- Long-term Debt Ratio

Control Variables
- Firm Size
- Profitability (ROA)
- Asset Tangibility
- Liquidity
- Sales Growth

Econometric Model
The regression model is specified as:
[FirmValue_{it}=\beta_0+\beta_1Leverage_{it}+\beta_2Profitability_{it}+\beta_3FirmSize_{it}+\beta_4Growth_{it}+\beta_5Tangibility_{it}+\varepsilon_{it}
]

Panel estimations include:
- Pooled OLS

- Fixed Effects Model
- Random Effects Model
- Hausman Test
- Generalized Method of Moments (GMM)

VI. RESULTS AND DISCUSSION

The empirical findings indicate that leverage significantly affects firm value. Moderate debt financing improves market valuation by providing tax advantages and managerial discipline. However, excessive leverage reduces firm value due to increased bankruptcy risk and financial distress.

Profitability exhibits a positive and statistically significant relationship with firm value, suggesting profitable firms generate higher investor confidence. Firm size also contributes positively to firm valuation because larger firms possess better access to financial markets and diversified operations.

Growth opportunities significantly enhance firm value, while excessive debt weakens investment capacity. Asset tangibility positively influences borrowing capacity but demonstrates only a moderate effect on market valuation.

The GMM estimation confirms the robustness of the findings after controlling for endogeneity and reverse causality.

Overall, the results strongly support the Trade-off Theory while providing partial support for the Pecking Order Theory.

VII. PRACTICAL IMPLICATIONS

The findings offer several practical implications:

- Managers should maintain an optimal debt-equity mix rather than maximizing leverage.
- Investors should evaluate firms' financing structures when making investment decisions.
- Policymakers should strengthen capital markets to improve firms' access to diversified financing sources.
- Financial institutions should consider firm-specific characteristics when designing lending policies.

VIII. CONCLUSION

This study investigates the relationship between capital structure decisions and firm value in emerging economies. The findings demonstrate that leverage significantly affects firm valuation, although the relationship is nonlinear. Moderate debt financing enhances firm value through tax benefits and improved managerial discipline, whereas excessive debt increases financial distress costs and reduces market valuation.

The results contribute to the growing literature on corporate finance by providing empirical evidence from emerging markets. The study confirms that financing decisions should balance the benefits and costs of debt while considering firm-specific and institutional characteristics.

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Future research may extend the analysis by incorporating environmental, social, and governance (ESG) factors, corporate governance variables, industry heterogeneity, and cross-country institutional differences.

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Work–Life Balance of Public Sector Bank Employees in Afghanistan: A Comprehensive Review of Global Evidence and Contextual Challenges

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***Abstract*—Work–life balance (WLB) has emerged as a crucial factor influencing employee well-being and organizational effectiveness in contemporary workplaces. This review paper synthesizes global theoretical and empirical literature on WLB with particular focus on public sector banking environments to develop contextual insights relevant to Afghanistan. Existing studies indicate that banking employees commonly face long working hours, heavy workloads, limited flexibility, and weak institutional support, resulting in work–life conflict, stress, and reduced job satisfaction. Comparative evidence from developing economies further highlights that bureaucratic rigidity and inadequate human resource policies hinder effective implementation of WLB initiatives. However, scholarly research on WLB in Afghanistan's public banking sector remains absent, revealing a significant contextual research gap. This review consolidates dominant theoretical perspectives and sector-specific challenges to provide a conceptual foundation for future empirical investigations. The study concludes by emphasizing the need for employee-centered human resource reforms to enhance well-being, productivity, and institutional effectiveness in Afghanistan's public banks.**

***Index Terms*—Work–Life Balance, Public Sector Banks, Afghanistan, Employee Well-being, Institutional Challenges, Literature Review.**

I. INTRODUCTION

The transformation of work environments in the twenty-first century has intensified job demands across service industries, particularly in financial institutions. Globalization, digital banking

systems, customer-driven performance metrics, and extended operational hours have substantially altered the nature of banking work (Clarke et al., 2004; Kossek et al., 2014). As a result, employees increasingly struggle to maintain equilibrium between professional responsibilities and personal life domains. Work–life balance (WLB) has therefore become a strategic human resource concern influencing employee wellbeing, organizational commitment, and institutional sustainability (Lockwood, 2003).

Work–life balance broadly refers to an individual's capacity to manage work and non-work responsibilities with minimal conflict and satisfactory performance in both domains (Hayman, 2005; Greenhaus & Allen, 2011). In banking institutions, employees encounter heavy workloads, time pressure, customer service demands, and compliance-driven administrative processes, making balance difficult to achieve (Tanvi & Fatama, 2012; Magotra, 2019). When imbalance persists, employees experience stress, burnout, absenteeism, and declining motivation, ultimately reducing service quality and organizational performance (Hobfoll, 1989; Nadeem & Abbas, 2009).

Empirical research across regions confirms that effective WLB practices improve job satisfaction, employee engagement, and retention (Greenhaus et al., 2003; Dev, 2012; Sindhuja & Subramanian, 2020). Conversely, inadequate WLB is associated with role conflict, turnover intentions, health problems, and reduced productivity (Mensah & Adjei, 2020; Soomro et al., 2018). Gender dimensions further compound the challenge, as women employees often face dual role pressures and limited institutional support (Smithson & Stokoe, 2005; Alqahtani, 2020).

In developing economies, systemic factors such as weak labor regulation, leadership inefficiencies, and limited HR capacity constrain implementation of effective WLB policies (Tamunomiebi & Oyibo, 2020; Akanji, 2012). Afghanistan represents a particularly under-researched context. Public banking institutions operate under rigid bureaucratic structures, limited technological integration, staffing shortages, and socio-economic instability. These realities intensify work demands while offering minimal flexibility or employee support mechanisms. Despite the global expansion of WLB research, scholarly investigation within Afghanistan's public banking sector remains virtually absent. This literature review therefore seeks to synthesize existing global knowledge while identifying contextual gaps relevant to Afghan public banks.

II. OBJECTIVES OF THE REVIEW

This review aims to:

1. Consolidate major global theoretical and empirical developments in work–life balance research.
2. Critically synthesize findings related to WLB in banking-sector employment.
3. Identify dominant global trends and recurring challenges.
4. Examine organizational and institutional factors shaping WLB.
5. Contextualize global evidence within Afghanistan's public banking sector.

6. Identify research gaps and propose a future research agenda.

III. METHOD OF LITERATURE IDENTIFICATION

A narrative literature review approach was adopted. Published studies on work–life balance were collected from peer-reviewed journals in organizational behavior, human resource management, banking studies, and development-sector research. Particular attention was given to studies examining banking-sector employees, public-sector work environments, gender dimensions, organizational support practices, and employee well-being outcomes. Both empirical and conceptual papers were included to develop an integrated thematic synthesis.

IV. CONCEPTUALIZATION OF WORK–LIFE BALANCE

Work–life balance has evolved from the earlier concept of work–family balance into a broader multidimensional construct encompassing professional, family, social, and personal life domains (Joseph & Sebastian, n.d.). Hayman (2005) conceptualized WLB as effective management of work and non-work demands, while Greenhaus and Allen (2011) emphasized satisfaction and low role conflict as core conditions. Joseph and Sebastian further argued that WLB better captures modern lifestyle demands beyond family responsibilities alone.

Modern organizational transformations, including technological connectivity and extended work availability, have intensified work demands, making WLB increasingly difficult to achieve (Lockwood, 2003; Kossek et al., 2014). As a result, WLB has evolved into a strategic human resource imperative, essential for sustaining employee well-being, motivation, and long-term organizational effectiveness (Igbinomwanhia et al., 2012).

Contemporary literature identifies time balance, engagement balance, and satisfaction balance as key dimensions of WLB (Ramos et al., 2015). Muafi et al. (2021) additionally introduced Islamic perspectives of WLB, emphasizing balance of time, participation, and satisfaction as essential for holistic wellbeing in faith-based societies. These conceptual expansions reflect the universal relevance of WLB across cultures and occupational settings.

Theoretical Perspectives Underpinning Work–Life Balance

Several theoretical frameworks explain the dynamics of WLB. Role theory suggests that competing demands between work and non-work domains produce inter-role conflict and stress (Edwards & Rothbard, 2000). Conservation of Resources theory posits that individuals experience stress when work obligations threaten personal resources such as time, energy, and family engagement (Hobfoll, 1989). Meanwhile, social support theory highlights the buffering role of organizational, supervisory, and family support in enabling WLB achievement (Abendroth & den Dulk, 2011; Uddin et al., 2020).

These theoretical models collectively suggest that WLB is shaped by organizational policies, leadership support, institutional culture, and external socio-economic conditions — factors particularly relevant in public-sector employment systems.

Work–Life Balance and Job Satisfaction

A substantial body of empirical evidence confirms a strong association between WLB and job satisfaction. Greenhaus et al. (2003) found that balanced employees report higher quality of life and workplace satisfaction. Malik and Jiaotong (n.d.) demonstrated that WLB mediates the relationship between job benefits and job satisfaction, indicating that compensation alone cannot ensure satisfaction without balance. Similarly, Shujat and Bhutto (2011) reported that employees in Karachi's banking sector remain dissatisfied despite stable employment when WLB is absent.

Studies across diverse contexts reinforce these findings. Yadav and Dabhade (2014) established that supportive work environments and employee-centered policies enhance WLB and satisfaction among banking and education workers. Fahlevi et al. (2020) confirmed that work pressure and long hours negatively influence satisfaction in Indonesia's banking sector. Hasan and Teng (2017) further showed that WLB significantly predicts job satisfaction across gender and ethnic groups in Malaysia. Collectively, these findings demonstrate that WLB functions as a core determinant of employee satisfaction across organizational settings.

Work–Life Balance and Employee Performance

Beyond satisfaction, WLB significantly influences employee performance and engagement. Lilian Obiageli et al. (2015) found that banking employees perform better when motivated by flexible leave and supportive HR practices. Oa (2018) confirmed that flexible work arrangements and social support predict positive behavioral outcomes including engagement and intention to stay. Similarly, Anthonia and Ukoha (2018) reported that flexible working hours significantly improve employee performance in Nigerian banks.

Further, Thevanes and Harikaran (2020) identified organizational citizenship behavior as a mediating mechanism linking WLB and organizational performance. Bataineh (2019) likewise found that happiness at work and WLB jointly enhance employee performance. These studies collectively affirm that balanced employees contribute more effectively to organizational productivity and service quality.

Work–Life Balance, Stress, and Turnover Intentions

Poor WLB is strongly associated with occupational stress and turnover intentions. Parker and DeCotiis (1983) identify workload and role conflict as key stressors in demanding occupations. Amazue and Onyishi (2016) found that Nigerian bank employees experience extended working hours and stress, directly affecting WLB outcomes. Javed et al. (2014) reported that job stress and role conflict increase turnover intentions when WLB is absent.

Empirical findings from Kaushalya and Perera (2018) and Fitria and Roza Linda (2019) demonstrate that improved WLB significantly reduces turnover intentions in banking

institutions. Sindhuja and Subramanian (2020) further confirmed that WLB directly influences employee retention in public and private banks. These findings underscore WLB's protective role against burnout and staff attrition.

Gender, Social Support, and Cultural Dimensions of Work–Life Balance

Gendered role expectations significantly shape WLB experiences. Smithson and Stokoe (2005) highlight how organizational cultures often impose gender-blind expectations that disadvantage women balancing professional and family roles. Tiwari (2017) and Pahuja (2017) found that female bank employees face disproportionate work–family pressures due to limited organizational support.

Cross-cultural studies further reveal that societal norms and institutional frameworks influence WLB practices. Mensah and Adjei (2020) showed that welfare state systems moderate the relationship between work-life conflict and health outcomes. Walga (2018) found significant cross-national variation in WLB and job satisfaction. Uddin et al. (2020) emphasized the importance of perceived social and supervisory support in enabling female bankers to achieve WLB in developing economies.

Work–Life Balance in the Banking Sector

The banking sector consistently emerges as a high-pressure occupational environment. Tanvi and Fatama (2012) and Chahal et al. (2013) identified heavy workloads, strict schedules, and customer service pressure as core WLB challenges for bank employees. Mordi et al. (2013) found that although WLB policies exist in Nigerian banks, utilization remains limited due to managerial resistance and cultural norms.

Lestari et al. (2021) confirmed that WLB policies improve loyalty and reduce turnover intentions in Indonesian banks. Magotra (2019) reported that public-sector bank employees experience lower productivity and higher stress due to rigid administrative structures. Collectively, global banking-sector research reveals consistent WLB challenges rooted in institutional rigidity, performance pressure, and limited flexibility.

Work–Life Balance in Public-Sector Institutions

Public-sector organizations typically operate within centralized bureaucratic frameworks, restricting flexible work arrangements and employee autonomy (H & A, 2018). Akanji (2012) observed that weak institutional governance and leadership failures obstruct WLB policy implementation in developing countries. Tamunomiebi and Oyibo (2020) further identified systemic barriers, including poor enforcement of employment standards and limited HR capacity.

These findings suggest that public-sector WLB challenges differ from private-sector settings due to structural and regulatory constraints — a condition highly relevant for Afghanistan's state-owned banking institutions.

Contextualizing Work–Life Balance in Afghanistan's Banking Sector

Despite growing international WLB scholarship, empirical evidence from Afghanistan remains almost entirely absent. Afghanistan's public banking institutions operate within fragile governance systems, limited technological infrastructure, and constrained HR development mechanisms. Employees experience high workloads, limited leave utilization, centralized decision-making, and minimal flexibility — conditions similar to those observed in other developing public-sector systems but intensified by institutional fragility.

Socio-cultural expectations further increase role pressures, particularly for female employees managing professional and family obligations. Yet formal WLB policies such as remote work, flexible scheduling, childcare support, or structured stress management programs remain largely unavailable. This absence of institutional support suggests a unique WLB environment distinct from contexts examined in existing banking-sector studies.

V. RESEARCH GAP AND FUTURE RESEARCH AGENDA

The reviewed literature confirms that work–life balance significantly influences job satisfaction, employee performance, turnover intentions, and organizational effectiveness across sectors and cultures. However, nearly all empirical research focuses on private-sector banking or stable institutional economies. Public-sector banking systems in fragile, conflict-affected, and institutionally constrained environments remain underexplored.

No prior study systematically examines work–life balance challenges within Afghanistan's public banking sector. This absence of empirical and conceptual evidence limits understanding of how institutional fragility, governance limitations, socio-cultural norms, and HR capacity interact to shape employee work–life outcomes. Consequently, future research should:

Research Gaps

The review identifies six key gaps:

1. Absence of empirical WLB studies in Afghanistan's banking sector.
2. Limited evidence on public-sector institutional constraints and WLB.
3. Lack of gender-focused WLB studies in conservative economies.
4. Insufficient integration of organizational effectiveness outcomes.
5. Limited longitudinal research on WLB sustainability.
6. Minimal exploration of cultural and religious influences on WLB perceptions.

Future Research Agenda

Future research should:

- Conduct empirical assessment of WLB in Afghanistan's public banks.
- Examine links between WLB, institutional effectiveness, and service quality.
- Investigate gender-responsive WLB interventions.
- Explore leadership and HR policy roles in WLB implementation.

• Integrate cultural and socio-religious dimensions into WLB frameworks.
• Develop localized policy models for public-sector reform.

VI. DISCUSSION

This literature review examined global and regional scholarship on work–life balance (WLB) with specific emphasis on banking sector employees, drawing particular relevance to the emerging public-sector banking context of Afghanistan. Across geographical and institutional settings, the reviewed studies consistently affirm that work–life balance is a critical determinant of employee well-being, job satisfaction, organizational commitment, and performance. However, the literature also reveals that the nature, intensity, and consequences of work–life imbalance differ significantly depending on socio-economic structures, institutional maturity, and labor market conditions.

Evidence from developed economies highlights the role of supportive institutional frameworks, flexible work arrangements, and welfare systems in enabling employees to achieve sustainable work–life integration (Abendroth & den Dulk, 2011; Greenhaus & Allen, 2011). In contrast, studies from developing and transitional economies, particularly within banking sectors in South Asia and Africa, reveal persistent challenges such as excessive workloads, rigid hierarchies, limited autonomy, weak labor protection, and inadequate human resource policies (Mordi et al., 2013; Shujat & Bhutto, 2011; Tamunomiebi & Oyibo, 2020). These conditions intensify work–family conflict, occupational stress, and reduced employee engagement.

A recurring theme across banking-sector research is that employees face extended working hours, performance pressure, customer service demands, and compliance burdens. While private banks often experience high performance-driven stress, public banks face additional challenges of bureaucratic rigidity, limited resources, outdated systems, and restricted career mobility. This distinction is particularly relevant to Afghanistan, where public banking institutions operate within fragile administrative infrastructures and constrained economic environments. Yet, despite these realities, empirical or conceptual studies focusing on Afghanistan's banking sector remain virtually absent in existing literature.

Another critical insight from the reviewed studies is that work–life balance is not solely an individual responsibility but is strongly shaped by organizational culture, leadership attitudes, institutional policies, and national labor governance. Several authors emphasize that even when WLB policies exist on paper, weak enforcement mechanisms, unsupportive management, and low employee awareness hinder effective implementation (Akanji, 2012; Lockwood, 2003). These systemic barriers are likely to be more pronounced in Afghanistan, where institutional oversight mechanisms and labor rights enforcement remain underdeveloped.

Furthermore, the literature indicates emerging trends such as remote work, flexible scheduling, and supportive supervisory practices as effective tools for improving WLB in banking institutions, particularly during crises such as the COVID-19 pandemic (Chandra Putra et al.,

2020). However, such adaptive practices remain largely unexplored in Afghan public sector institutions, revealing an important future research opportunity.

Overall, the reviewed studies collectively suggest that improving work–life balance in banking institutions contributes not only to employee satisfaction but also to enhanced organizational productivity, reduced turnover, improved service quality, and stronger institutional effectiveness. However, the absence of Afghanistan-specific empirical or policy-oriented research creates a major contextual gap. This review therefore establishes a theoretical and evidential foundation for future empirical investigations into work–life balance challenges within Afghanistan's public banking system.

VII. CONCLUSION

This literature review synthesized existing scholarship on work–life balance in organizational and banking-sector contexts to develop an informed understanding of challenges relevant to Afghanistan's public banking institutions. The review confirms that work–life balance is a multidimensional construct shaped by workload demands, organizational culture, leadership support, institutional policies, and national labor structures. Across global evidence, balanced integration of professional and personal roles consistently emerges as a key predictor of employee well-being, job satisfaction, commitment, and performance.

The review further demonstrates that banking employees, particularly in developing economies, face intensified work–life imbalance due to long working hours, limited flexibility, performance pressure, and weak institutional support systems. These challenges are likely to be more severe in Afghanistan's public banking sector, where bureaucratic rigidity, resource limitations, and evolving governance frameworks constrain the adoption of progressive human resource practices.

A major conclusion of this review is that current literature inadequately addresses the Afghan context. No systematic empirical research exists on work–life balance within Afghanistan's public banking institutions, leaving policymakers and administrators without evidence-based guidance. This gap presents a strong justification for future empirical studies that examine work–life balance dynamics, institutional barriers, and policy interventions tailored to Afghanistan's socio-economic and administrative realities.

Finally, the review underscores that achieving sustainable work–life balance in public banking institutions requires integrated strategies, including flexible work arrangements, supportive leadership training, fair workload distribution, employee assistance programs, and strengthened labor policy enforcement. Prioritizing these initiatives is likely to improve employee well-being, organizational productivity, and institutional effectiveness, contributing to broader public sector reform and financial service development in Afghanistan.

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NEP 2020 and the Constitutional Reconfiguration of Higher Education in India: A Jurisprudential Analysis of Governance, Equity, and Global Alignment

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***Abstract*—The National Education Policy (NEP) 2020 marks a constitutional reconfiguration of higher education governance in India, extending beyond administrative reform to reshape the constitutional, legal, and institutional architecture through which the sector is governed. Anchored in Articles 14, 21A, 41, and 45 of the Constitution of India and situated within the Concurrent List, the policy engages the constitutional principles of substantive equality, cooperative federalism, institutional autonomy, and constitutional morality. This investigation relies on a doctrinal legal research design informed through constitutional analysis and comparative jurisprudence to examine four interrelated dimensions: the constitutional foundations of NEP 2020; the evolving regulatory framework envisaged under the Higher Education Commission of India (HECI) and implemented through successive University Grants Commission (UGC) reforms; the policy's alignment with contemporary transnational university education governance; and the constitutional implications of digital governance. The doctrinal analysis demonstrates that implementation initiatives - including the Curriculum and Credit Framework for Undergraduate Programmes (CCFUP), the Four-Year Undergraduate Programme (FYUGP), the Academic Bank of Credits (ABC), Multiple Entry - Multiple Exit (MEME), Automated Permanent Academic Account Registry (APAAR), and other digital governance mechanisms- have progressively operationalized constitutional principles through learner-centred, accountability-oriented regulatory reforms. While these developments strengthen transparency, academic mobility, institutional accountability, and global engagement, persistent concerns relating to regulatory centralization, fiscal disparities among States, digital inequality, data governance, and cooperative federalism continue to present unresolved constitutional challenges. The study concludes that NEP 2020 should be understood as an evolving constitutional project whose long-term legitimacy depends upon balanced federal implementation, constitutional accountability, and the continued protection of equality, institutional autonomy, and**

fundamental rights within an increasingly digital and globally interconnected advanced education system.

***Index Terms*—NEP 2020; Constitutionalism; Cooperative Federalism; Higher Education Governance; Digital Governance; Comparative Jurisprudence**

I. INTRODUCTION

Education occupies a constitutionally significant position within India's governance framework. The Forty-second Constitutional Amendment placed education in the Concurrent List, establishing shared responsibility between the Union and the States. Judicial interpretation of Articles 14 and 21A has further reinforced the State's constitutional obligation to ensure equitable access to education, thereby positioning advanced education as an important instrument for advancing substantive equality, human development, and social justice.

Within this regulatory framework, the NEP 2020 represents more than an executive policy; it seeks to reconfigure the legal and institutional architecture of higher education governance in India. Initial academic evaluations regarded NEP 2020 as India's most far-reaching educational reform introduced in recent decades, emphasizing multidisciplinary education, institutional autonomy, research orientation, academic flexibility, and governance modernization as its defining features (Aithal & Aithal, 2020; Tilak, 2021). As implementation has progressed, recent scholarships have further observed that the policy has evolved beyond a broad reform agenda into an increasingly integrated regulatory framework that promotes learner-centred education, quality assurance, academic mobility, digital governance, and competency-based learning through successive implementation measures (Sivaraman et al., 2026).

Since 2020, the UGC has progressively operationalized key components of NEP 2020 through initiatives such as the CCFUP, the ABC, the FYUGP, MEME, the National Higher Education Qualifications Framework (NHEQF), and other implementation frameworks. These developments illustrate a gradual transition from policy formulation to regulatory implementation, reflecting an evolving governance philosophy centred on institutional accountability, academic flexibility, learner mobility, and quality enhancement.

Despite the growing literature on educational reform and policy implementation, comparatively limited scholarly attention has been devoted to examining NEP 2020 as an evolving constitutional project. Much of the existing literature evaluates pedagogical innovation, institutional restructuring, or implementation challenges, whereas relatively few studies systematically analyse the constitutional implications of the policy in relation to substantive equality, cooperative federalism, institutional autonomy, constitutional morality, and digital governance. This study addresses that gap by adopting a doctrinal constitutional approach to examine how NEP 2020 and its subsequent regulatory implementation have reshaped college education governance within India's constitutional framework.

Accordingly, this study argues that NEP 2020 should be understood not merely as an education policy but as grounded in the principles of substantive equality, cooperative federalism, institutional autonomy, and constitutional morality. By examining the constitutional foundations of the policy, the evolving regulatory framework, comparative global developments, and emerging challenges of digital governance, this inquiry offers valuable insights into growing discourse on the constitutional governance of university education and the future trajectory of educational reform in India.

II. RESEARCH OBJECTIVES

This study is undertaken with the following objectives:
i. To examine the constitutional foundations of NEP 2020, with particular reference to substantive equality and cooperative federalism.
ii To analyze the constitutional implications of the evolving higher education regulatory framework under NEP 2020 and successive UGC reforms.
iii To evaluate the alignment of India's higher education governance with comparative and transnational regulatory frameworks while preserving constitutional identity.
iv. To examine the constitutional implications of digital governance under NEP 2020, with particular reference to privacy, data governance, and digital inclusion.

III. RESEARCH METHODOLOGY

The present investigation is methodologically relied on doctrinal legal inquiry, drawing upon constitutional analysis, normative evaluation, and comparative legal jurisprudence. Primary sources include the Constitution of India, the NEP 2020, statutory and regulatory instruments, judicial decisions, UGC implementation frameworks, and official policy notifications issued between 2020 and mid-2026. Secondary sources include contemporary academic literature, policy analyses, and comparative studies on governance frameworks and university education regulation. The study employs constitutional-doctrinal analysis, supported by a thematic synthesis of contemporary scholarly literature, to examine the implementation of NEP 2020 through the constitutional principles of substantive equality, cooperative federalism, institutional autonomy, constitutional morality, and digital governance. Comparative analysis of selected international college education frameworks is undertaken to contextualize India's evolving regulatory reforms within broader global developments. As a qualitative doctrinal inquiry, the study does not rely on empirical data; rather, it evaluates the institutional legitimacy, regulatory evolution, and jurisprudential implications of NEP 2020 within the framework of Indian constitutional law.

IV. SCOPE AND LIMITATIONS

This study is confined to a doctrinal constitutional analysis of the NEP 2020 and its implementation within the constitutional structure of India, statutory and regulatory instruments, judicial decisions,

UGC regulatory frameworks, and official policy notifications issued up to mid-2026. The analysis focuses on the constitutional dimensions of post-secondary education governance, particularly substantive equality, cooperative federalism, institutional autonomy, constitutional morality, comparative constitutional alignment, and digital governance.

The study does not undertake an empirical evaluation of policy implementation, institutional performance, stakeholder perceptions, or educational outcomes through surveys, interviews, case studies, or quantitative methods. Accordingly, its findings should be understood as normative constitutional interpretations rather than empirical assessments of the effectiveness of NEP 2020. While selected international tertiary education frameworks are considered for comparative constitutional analysis, the primary focus remains on the Indian constitutional and regulatory context. Future research may complement the present doctrinal inquiry through empirical, comparative, and interdisciplinary studies examining the execution and impact of NEP 2020 within Indian universities, States, and diverse stakeholder groups.

V. CONSTITUTIONAL FOUNDATIONS OF NEP 2020

The constitutional validity of the NEP 2020 is best understood through the foundational principles of the Constitution of India. Rather than functioning merely as an education policy, the framework engages multiple constitutional doctrines relating to equality, federalism, Directive Principles of State Policy, constitutional morality, and transformative constitutionalism. Contemporary scholarship recognizes that university education regulation in India has historically evolved through constitutional principles balancing institutional autonomy, public accountability, and State responsibility rather than through purely administrative control (Saxena, 2025). Similarly, constitutional governance literature emphasizes that educational reforms derive long-term legitimacy not only from statutory authority but also from their consistency with constitutional values, democratic accountability, and the rule of law (Khosla, 2020). Against this constitutional backdrop, the following discussion examines the foundational principles underpinning NEP 2020.

5.1 Substantive Equality and Educational Access

Article 14 guarantees equality before the law, while contemporary constitutional interpretation recognizes substantive equality as requiring affirmative measures to address structural disadvantages and ensure meaningful access to opportunities. NEP 2020 operationalizes this constitutional principle by promoting inclusive access, enhancing student enrolment levels, strengthening the higher learning sector in underserved regions, and encouraging flexible learning pathways.

By embedding inclusion within its regulatory framework, NEP 2020 reflects a distributive approach to university education governance, positioning educational reform as an instrument of social justice consistent with constitutional morality. In this respect, the policy reinforces the constitutional understanding that tertiary education regulation must simultaneously promote educational excellence, equitable opportunity, and institutional accountability within a rights-based governance framework (Saxena, 2025). Recent scholarship likewise observes that the

successful implementation of NEP 2020 requires inclusive governance capable of reducing educational disparities while ensuring equitable participation across diverse social and regional contexts (Kumar & Choudhury, 2022).

5.2 Directive Principles and Human Development

Articles 41 and 45 impose a constitutional obligation upon the State to promote educational welfare. Although non-justiciable, these Directive Principles provide important guidance for governance and public policy. NEP 2020 advances this constitutional vision by linking educational reform with social mobility, research, skill development, innovation, and human development.

The policy therefore reinforces education as both a public good and a constitutional instrument for inclusive socio-economic development. Its emphasis on multidisciplinary learning, lifelong education, institutional capacity-building, and learner-centred education reflects the broader constitutional objective of promoting human development through inclusive educational opportunities to quality higher education. International policy literature similarly recognizes university education as a fundamental catalyst for achieving sustainable development, human capital formation, innovation, and inclusive economic growth (UNESCO, 2021; World Bank, 2022), thereby reinforcing the constitutional aspirations reflected in the Directive Principles of State Policy.

5.3 Cooperative Federalism

Education's inclusion in the Concurrent List requires shared governance between the Union and the States. Although the HECI has not yet replaced the existing statutory framework, its governance philosophy increasingly informs successive UGC reforms. This evolving regulatory architecture promotes accountability, institutional flexibility, academic quality, and learner mobility while simultaneously raising constitutional questions concerning federal balance and institutional autonomy.

Recent constitutional scholarship observes that the legitimacy of tertiary education governance depends upon maintaining an appropriate balance between national regulatory objectives and the constitutional autonomy of educational institutions within India's federal framework (Saxena, 2025). Likewise, Khosla (2020) argues that constitutional governance reforms in a federal democracy must reconcile national coordination with meaningful State participation and institutional diversity. These perspectives are particularly relevant to NEP 2020, whose successful implementation depends upon cooperative engagement between the Union, the States, regulatory authorities, and tertiary education institutions.

The normative legitimacy of these reforms therefore depends upon preserving cooperative federalism through meaningful State participation and adaptability in implementation. Differences in legislative frameworks, fiscal resources, administrative capacity, and digital infrastructure continue to influence the implementation of reforms such as the FYUGP, MEME, and the ABC. Consequently, the long-term constitutional success of NEP 2020 requires balancing nationally

coordinated standards with institutional autonomy, federal flexibility, and equitable educational opportunity.

5.4 Constitutional Morality and Transformative Constitutionalism

The institutional legitimacy of NEP 2020 extends beyond administrative reform and must also be examined through constitutional morality and transformative constitutional principles. The essence of these doctrines lies in ensuring that constitutional governance continuously advances the values of equality, justice, liberty, fraternity, and dignity by responding effectively to changing societal, economic, and technological conditions. Contemporary legal scholarship similarly recognizes constitutional morality as an evolving interpretative doctrine that guides public institutions towards governance consistent with constitutional values rather than transient political or majoritarian preferences (Srivastava, 2023). Likewise, transformative constitutionalism views constitutional rights as dynamic instruments for achieving substantive justice and inclusive governance (Jain & Girish, 2023).

The Supreme Court has consistently affirmed this constitutional approach. In Justice K.S. Puttaswamy (Retd.) v. Union of India (2017), the Court recognized privacy as a fundamental right under Article 21 and reaffirmed the Constitution as a living document protecting dignity, autonomy, and individual development. Similarly, in Navtej Singh Johar v. Union of India (2018), the Supreme Court affirmed the primacy of constitutional morality over societal norms, emphasizing that State action must remain anchored in constitutional values rather than majoritarian preferences.

Viewed through this jurisprudential framework, NEP 2020 represents more than an educational policy. It functions as a transformative constitutional instrument that seeks to operationalize substantive equality, inclusive access, institutional autonomy, human development, and digital inclusion through systemic reform of higher education. Its long-term regulatory legitimacy therefore depends not only on effective implementation but also on continued adherence to constitutional morality, protection of fundamental rights, preservation of India's cooperative federal structure, and a regulatory framework that remains faithful to constitutional principles governing college education (Saxena, 2025).

VI. REGULATORY TRANSFORMATION AND GOVERNANCE

The NEP 2020 reflects a fundamental reorientation in tertiary education governance from a compliance-driven regulatory model towards one emphasizing accountability, institutional autonomy, quality assurance, and learner-centred governance. While early scholarship primarily examined the policy's reform agenda (Tilak, 2021), subsequent implementation has increasingly focused on regulatory restructuring, learner mobility, digital governance, and institutional accountability (Sivaraman et al., 2026). Rather than merely restructuring administration, the policy is designed to restructure the university education regulation through transparency, flexibility, and evidence-based governance consistent with constitutional principles of equality and fairness. Early

scholarly assessments similarly characterized NEP 2020 as a comprehensive governance reform intended to transform institutional structures, multidisciplinary education, academic flexibility, and research culture in Indian university education (Aithal & Aithal, 2020). More recent scholarship further identifies NEP 2020 as a transformative regulatory framework that seeks to enhance institutional quality, learner mobility, multidisciplinary education, and skill development through progressive governance reforms (Sivaraman et al., 2026).

Although the HECI has not yet replaced the existing statutory framework, its governance philosophy increasingly informs successive UGC reforms. Initiatives including the CCFUP, the ABC, the National Credit Framework (NCrF), MEME, the FYUGP, and revised quality assurance mechanisms demonstrate a gradual transition towards the regulatory framework envisaged under NEP 2020. As observed in recent systematic reviews, these implementation initiatives collectively represent a gradual but significant restructuring of India's tertiary education governance rather than isolated policy interventions (Sivaraman et al., 2026).

The proposed HECI model separates regulation, accreditation, funding, and academic standard-setting through four specialized verticals - NHERC, NAC, HEGC, and GEC. Although these institutions remain subject to future legislation, recent UGC reforms increasingly reflect their underlying governance philosophy by promoting institutional accountability, academic flexibility, learner mobility, and simplified regulatory processes.

From a constitutional perspective, these reforms strengthen the principles of non-arbitrariness, procedural fairness, and institutional accountability under Article 14 while encouraging greater academic autonomy. Their constitutional legitimacy, however, depends upon preserving cooperative federalism, institutional diversity, meaningful participation of the States, and equitable implementation across institutions with varying capacities and resources.

The following subsections examine four major implementation initiatives - ABC, APAAR, FYUGP, and MEME - that collectively illustrate how constitutional principles of substantive equality, academic mobility, institutional autonomy, and regulatory accountability are progressively operationalized through successive UGC reforms.

6.1 Academic Bank of Credits (ABC) and Digital Academic Mobility

The ABC, introduced through the University Grants Commission, Regulations of 2021, establishes a nationally interoperable digital repository that enables students to earn, carry forward, and utilize academic credits obtained from accredited institutions of higher learning. Together with the NCrF, ABC promotes academic mobility, multidisciplinary learning, lifelong education, and greater interoperability across diverse educational pathways.

From a constitutional perspective, ABC advances substantive equality by reducing institutional barriers to educational access and learner mobility. It also aligns India's higher learning framework with internationally recognized principles of credit portability and flexible learning, demonstrating the transition of NEP 2020 from policy formulation to operational regulatory practice. By facilitating lifelong learning and recognition of prior learning, ABC also reflects emerging international approaches to competency-based education and learner-centred governance.

6.2 Digital Academic Identity: APAAR and National Academic Depository

The ABC has been complemented by the APAAR, which provides learners with a lifelong digital academic identity integrating academic credits, qualifications, and institutional records. Together with the National Academic Depository and DigiLocker, APAAR strengthens the portability, verification, and long-term preservation of academic credentials while improving administrative efficiency and institutional transparency.

Although these initiatives significantly enhance learner mobility and digital governance, they also raise constitutional concerns relating to informational privacy, data governance, cybersecurity, and institutional accountability. Following Justice K.S. Puttaswamy (Retd.) v. Union of India (2017), digital academic governance must operate within the constitutional principles of legality, proportionality, transparency, and informed consent to ensure that technological innovation remains consistent with the protection of individual autonomy and personal information. As digital governance continues to expand under NEP 2020, these safeguards assume increasing constitutional significance.

6.3 Four-Year Undergraduate Programme (FYUGP)

Implemented through the UGC CCFUP, the FYUGP promotes multidisciplinary education, flexible curricular pathways, undergraduate research, and multiple exit options. By expanding academic flexibility and encouraging research-oriented learning, FYUGP strengthens both educational quality and international academic mobility.

Recent scholarship identifies multidisciplinary curricula, competency-based education, flexible learning pathways, and skill-oriented education as defining features of NEP 2020's higher education reforms (Sivaraman et al., 2026). Likewise, Sharma and Bhardwaj (2021) argue that competency-based education represents a significant pedagogical shift towards outcome-oriented learning, while Mehrotra (2021) highlights the importance of integrating vocational education and employability skills within multidisciplinary higher education.

Constitutionally, FYUGP advances substantive equality by providing learners with greater academic flexibility while reinforcing institutional autonomy through curriculum design responsive to regional, disciplinary, and societal needs. The programme therefore supports the constitutional objective of promoting human development through an inclusive, learner-centred, and knowledge-driven post-secondary education system.

6.4 Multiple Entry–Multiple Exit (MEME)

The MEME framework enables learners to enter and exit higher learning at different stages while receiving appropriate academic qualifications. Supported by the Academic Bank of Credits and the National Credit Framework, it recognizes diverse educational pathways and accommodates varying personal, professional, and economic circumstances.

By preserving previously earned academic credits and facilitating re-entry into higher education, MEME operationalizes constitutional commitments to substantive equality, lifelong learning, and equitable educational opportunity. It reflects internationally recognized approaches to flexible

learning pathways, competency-based education, and learner mobility while accommodating the diverse educational needs of India's heterogeneous student population. Contemporary scholarship similarly emphasizes that flexible academic pathways and inclusive implementation are central to realizing the transformative objectives of NEP 2020 (Kumar & Choudhury, 2022; Sivaraman et al., 2026).

VII. COMPARATIVE JURISPRUDENCE AND GLOBAL ALIGNMENT

The constitutional transformation envisaged under the National NEP 2020 must be understood within the broader context of contemporary post-secondary education governance. As higher education systems increasingly emphasize quality assurance, academic mobility, institutional accountability, digital innovation, and international collaboration, comparative jurisprudence provides an important framework for evaluating India's regulatory reforms. Comparative scholarship recognizes that successful higher education reforms increasingly balance international competitiveness with national constitutional priorities and institutional diversity (Altbach & de Wit, 2021). While NEP 2020 reflects internationally recognized governance practices, it simultaneously preserves India's constitutional values, educational priorities, and cultural identity.

7.1 Transnational Regulatory Convergence

Contemporary university education governance increasingly promotes multidisciplinary education, academic credit portability, learner mobility, competency-based learning, and accountability-oriented quality assurance. NEP 2020 incorporates these principles, aligning Indian tertiary education with evolving international regulatory practices while integrating Indian Knowledge Systems and constitutional commitments to substantive equality, cooperative federalism, and social justice. Accordingly, the policy represents constitutional adaptation rather than the wholesale transplantation of foreign educational models.

International policy frameworks similarly emphasize that higher education governance should promote academic excellence while ensuring equitable access, lifelong learning, institutional accountability, and sustainable development (OECD, 2021; UNESCO, 2022). NEP 2020 reflects these global priorities through reforms designed to strengthen multidisciplinary education, research, innovation, and learner mobility within India's legal framework.

7.2 Comparative Credit Frameworks and Global Academic Mobility

The ABC reflects principles comparable to the European Credit Transfer and Accumulation System (ECTS) developed under the European Higher Education Area (EHEA), facilitating academic credit accumulation, transfer, and learner mobility across institutions. Likewise, the FYUGP, MEME, and the NCrF demonstrate convergence with international trends emphasizing competency-based learning, lifelong education, flexible academic pathways, and recognition of prior learning (Council of Europe & European Commission, 2020).

The growing recognition of digital credentials, micro-credentials, and interoperable academic records has further strengthened global academic mobility. India's implementation of the ABC, APAAR, DigiLocker, and the National Academic Depository reflects these developments by promoting secure credential verification, academic portability, and cross-institutional recognition. The European Commission's European approach to micro-credentials similarly illustrates the growing international acceptance of flexible and digitally verifiable learning pathways that support lifelong learning and workforce mobility (European Commission, 2023). Eventually, the regulatory legitimacy of India's digital academic ecosystem depends upon protecting informational privacy, transparency, procedural fairness, and equitable access to digital infrastructure.

The UNESCO Global Convention on the Recognition of Qualifications concerning Higher Education (2023) further reinforces international cooperation through the fair, transparent, and non-discriminatory recognition of academic qualifications. NEP 2020 demonstrates increasing compatibility with these global developments while continuing to operate within India's constitutional framework.

From a comparative constitutional perspective, NEP 2020 illustrates a process of selective constitutional adaptation rather than regulatory transplantation. International principles relating to academic mobility, quality assurance, digital governance, lifelong learning, and recognition of qualifications have been incorporated in a manner consistent with India's constitutional commitments to substantive equality, cooperative federalism, institutional autonomy, social justice, and the promotion of Indian Knowledge Systems. Consequently, comparative constitutional learning strengthens domestic educational reform while preserving constitutional identity, democratic accountability, and national sovereignty (Altbach & de Wit, 2021).

VIII. DIGITAL GOVERNANCE AND CONSTITUTIONAL ACCOUNTABILITY

The implementation of the NEP 2020 has established digital governance as a central component of higher education regulation in India. Digital initiatives such as the ABC, APAAR, DigiLocker, the National Academic Depository, and technology-enabled quality assurance systems have strengthened learner mobility, institutional transparency, and evidence-based governance. Consequently, digital governance under NEP 2020 extends beyond administrative modernization to become an important constitutional dimension of higher education regulation. Contemporary international policy literature similarly recognizes digital transformation as an essential component of resilient, inclusive, and learner-centred higher education systems (UNESCO, 2022; World Bank, 2022).

As educational administration becomes increasingly dependent on digital platforms, constitutional concerns relating to informational privacy, data protection, equality, institutional accountability, and algorithmic decision-making assume greater significance. The normative legitimacy of digital governance therefore depends upon ensuring that technological innovation remains consistent with the principles of dignity, equality, procedural fairness, transparency, and the rule of law.

8.1 Digital Public Infrastructure and Academic Mobility

The integration of the ABC, APAAR, DigiLocker, and the National Academic Depository has established a Digital Public Infrastructure (DPI) for higher education. These interoperable systems facilitate secure academic record management, credential verification, learner mobility, and recognition of academic achievements while supporting flexible learning pathways and institutional accountability. Beyond improving administrative efficiency, this digital architecture strengthens learner-centred governance and contributes to the realization of multidisciplinary and lifelong learning envisaged under NEP 2020. Similar digital credential ecosystems are increasingly being adopted internationally to support interoperable qualifications, lifelong learning, and cross-border academic mobility (European Commission, 2023).

8.2 Informational Privacy and Data Governance

The increasing digitization of higher education raises important constitutional questions concerning informational privacy and the governance of educational data. Following the Supreme Court's decision in Justice K.S. Puttaswamy (Retd.) v. Union of India (2017), privacy forms an integral component of Article 21 and imposes constitutional obligations upon public authorities responsible for collecting and processing personal information. These constitutional protections have acquired additional statutory significance through the Digital Personal Data Protection Act, 2023, which establishes principles governing lawful processing, purpose limitation, data security, and accountability in the handling of digital personal data.

Accordingly, digital governance mechanisms within higher education must operate consistently with the constitutional principles of legality, proportionality, transparency, informed consent, and institutional accountability to ensure that technological efficiency does not compromise individual autonomy or fundamental rights.

8.3 Cybersecurity and Institutional Accountability

As higher education increasingly relies upon interconnected digital platforms, cybersecurity has become an important constitutional concern. Data breaches, identity theft, cyber-attacks, and unauthorized access to academic databases may undermine public confidence in educational governance and compromise institutional integrity. Universities and regulatory authorities must therefore establish robust cybersecurity frameworks incorporating secure data management, periodic security audits, effective grievance-redress mechanisms, clearly defined institutional responsibilities, and appropriate incident-response protocols. Such safeguards reinforce constitutional principles of transparency, accountability, and the rule of law while strengthening trust in digitally enabled public institutions.

8.4 Digital Inclusion and Substantive Equality

The constitutional legitimacy of digital governance ultimately depends upon equitable access to technological infrastructure. Although digital platforms expand educational opportunities, disparities in digital infrastructure, institutional capacity, internet connectivity, and technological

accessibility continue to influence the implementation of technology-enabled reforms across India. Article 14 therefore requires that digital transformation promotes substantive equality rather than reinforcing existing socio-economic inequalities. International policy literature similarly students to earn, carry forward, and utilize academic credits obtained from accredited institutions of higher learning by investments in digital infrastructure, institutional capacity, faculty development, and inclusive access to ensure that technological innovation advances educational equity and sustainable development (UNESCO, 2022; World Bank, 2022).

8.5 Artificial Intelligence and Emerging Constitutional Challenges

Artificial Intelligence (AI) is increasingly reshaping higher education through adaptive learning, automated assessment, predictive analytics, administrative automation, and generative AI applications. While these technologies offer significant opportunities for improving educational quality and administrative efficiency, they also generate constitutional concerns relating to fairness, transparency, algorithmic bias, academic integrity, explainability, and accountability. Constitutional principles of equality, procedural fairness, and non-arbitrariness require that AI-assisted educational decisions remain subject to meaningful human oversight and effective accountability mechanisms.

Universities should therefore develop comprehensive institutional policies governing the responsible use of AI, academic honesty, intellectual property, data governance, and ethical research practices to ensure that technological innovation remains consistent with constitutional values and the protection of fundamental rights.

8.6 Digital Constitutionalism

The continuing implementation of NEP 2020 demonstrates that digital governance has evolved into a distinct constitutional dimension of higher education regulation. Digital identity, interoperable academic records, AI-enabled governance, cybersecurity, and learner-centred regulation collectively illustrate the emergence of a technology-driven governance framework grounded in constitutional accountability. The long-term legitimacy of this framework will depend not only upon administrative efficiency but also upon its ability to preserve equality, privacy, transparency, academic autonomy, cooperative federalism, procedural fairness, and responsible data governance.

Viewed through the emerging doctrine of digital constitutionalism, NEP 2020 illustrates how constitutional values continue to shape the governance of digitally enabled public institutions. As higher education becomes increasingly digital and globally interconnected, public governance must evolve alongside technological innovation to ensure that educational modernization remains firmly anchored in the enduring constitutional principles of justice, dignity, equality, and the rule of law.

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IX. PRINCIPAL FINDINGS

The constitutional, jurisprudential, and comparative analysis undertaken in this study yields four principal findings corresponding to the stated research objectives.

First, NEP 2020 represents a significant regulatory transformation in higher education governance by operationalizing the principles of substantive equality, cooperative federalism, constitutional morality, and transformative constitutionalism. The policy seeks to translate constitutional commitments relating to equitable access, institutional autonomy, multidisciplinary education, and human development into an evolving regulatory framework. However, the realization of these constitutional objectives depends upon balanced implementation across the Union and the States, taking into account differences in institutional capacity, fiscal resources, legislative frameworks, and digital readiness.

Second, the implementation of NEP 2020 demonstrates a gradual transition towards the governance philosophy envisaged under the proposed HECI. Although the UGC continues to function as the principal regulatory authority, successive reforms increasingly reflect a regulatory model emphasizing accountability, transparency, academic flexibility, learner mobility, and institutional autonomy. The institutional legitimacy of this transition depends upon preserving cooperative federalism, procedural fairness, institutional diversity, and meaningful participation of the States.

Third, NEP 2020 demonstrates increasing convergence between Indian higher education governance and contemporary international regulatory practices through academic mobility, multidisciplinary education, flexible learning pathways, digital governance, quality assurance, and recognition of qualifications. While these reforms align India's higher education system with evolving global standards, they simultaneously preserve constitutional commitments to social justice, public welfare, federal balance, and the promotion of Indian Knowledge Systems, reflecting a process of selective constitutional adaptation rather than regulatory transplantation.

Fourth, the expansion of digital governance under NEP 2020 has introduced new legal dimensions relating to informational privacy, data governance, equality, transparency, accountability, cybersecurity, and digital inclusion. Although technology-enabled governance enhances learner mobility, institutional efficiency, and regulatory effectiveness, its constitutional sustainability depends upon ensuring equitable digital access, responsible data governance, robust cybersecurity safeguards, and the protection of substantive equality, privacy, and procedural fairness in accordance with Articles 14 and 21 of the Constitution.

Taken together, these findings demonstrate that NEP 2020 has progressively operationalized constitutional principles through regulatory modernization and governance reform. Its long-term legitimacy will depend upon integrating constitutional values with effective implementation, balanced federal participation, regulatory accountability, digital constitutionalism, and adaptive governance capable of responding to technological, institutional, and societal change while remaining faithful to the constitutional principles of justice, equality, dignity, and the rule of law.

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X. DOCTRINAL FINDINGS IN RELATION TO THE RESEARCH OBJECTIVES

The foregoing analysis confirms that the NEP 2020 has evolved beyond a policy framework into an ongoing constitutional project that progressively reshapes higher education governance in India. Rather than creating an entirely new legal order, its implementation operationalizes constitutional principles through regulatory modernization, learner-centred governance, digital transformation, and institutional accountability. The doctrinal findings presented below synthesize the constitutional outcomes corresponding to each of the four research objectives.

Objective 1

The doctrinal analysis indicates that NEP 2020 advances the constitutional principles of substantive equality and cooperative federalism by promoting equitable educational access, learner mobility, institutional flexibility, multidisciplinary education, and human development. These reforms reflect a distributive understanding of equality consistent with Article 14 and the Directive Principles of State Policy while strengthening the constitutional objective of expanding access to quality education.

Meanwhile, the constitutional realization of these objectives depends upon effective cooperation between the Union and the States. Differences in institutional capacity, fiscal resources, digital infrastructure, and legislative frameworks continue to influence implementation. Accordingly, the long-term constitutional sustainability of NEP 2020 requires preserving cooperative federalism, institutional autonomy, and equitable educational opportunity alongside nationally coordinated quality standards.

Objective 2

The constitutional evaluation suggests that, although the proposed HECI has not yet replaced the existing statutory framework, its governance philosophy increasingly informs us of successive UGC reforms. This evolving regulatory model emphasizes transparency, accountability, academic flexibility, learner mobility, institutional autonomy, and administrative rationalization, thereby reinforcing the constitutional principles of non-arbitrariness, procedural fairness, and accountable governance under Article 14.

Its regulatory legitimacy, however, depends upon avoiding excessive centralization by preserving meaningful participation of the States, institutional diversity, cooperative federalism, judicial oversight, and regulatory accountability throughout the implementation process.

Objective 3

The present analysis confirms that NEP 2020 increasingly aligns India's higher education governance with contemporary international regulatory developments relating to academic mobility, competency-based learning, quality assurance, digital governance, lifelong learning, and recognition of qualifications. This convergence reflects a process of selective constitutional adaptation rather than regulatory transplantation.

Rather than replicating foreign educational models, NEP 2020 selectively incorporates internationally accepted regulatory principles while preserving constitutional commitments to substantive equality, cooperative federalism, institutional autonomy, social justice, and the promotion of Indian Knowledge Systems. The findings therefore demonstrate that comparative constitutional learning can strengthen domestic educational governance while preserving constitutional identity, democratic accountability, and national educational priorities.

Objective 4

The findings reveal that digital governance has emerged as an integral constitutional dimension of higher education regulation. Digital academic infrastructure strengthens learner mobility, institutional accountability, transparency, and regulatory efficiency while simultaneously raising constitutional concerns relating to informational privacy, responsible data governance, cybersecurity, artificial intelligence, and digital inclusion.

The constitutional sustainability of digital governance therefore depends upon ensuring that technological innovation remains consistent with the principles of equality, privacy, procedural fairness, transparency, accountability, and the rule of law. Long-term legitimacy requires robust legal safeguards, responsible governance of educational data, meaningful human oversight of AI-assisted decision-making, and equitable digital access to ensure that technological modernization remains consistent with constitutional values and the protection of fundamental rights.

10.1 Policy Implications

The constitutional analysis undertaken in this study carries several implications for the future implementation of NEP 2020. First, regulatory reforms should continue to strengthen cooperative federalism by ensuring meaningful participation of the States in higher education governance while maintaining nationally coordinated academic standards. Second, the progressive transition towards the governance philosophy envisaged under the proposed HECI should preserve institutional autonomy, procedural fairness, and transparent regulatory oversight to reinforce public confidence in higher education institutions.

Third, the continued expansion of digital governance requires robust implementation of privacy safeguards, responsible data governance, cybersecurity measures, and institutional accountability to ensure that technology-enabled reforms remain consistent with constitutional guarantees under Articles 14 and 21. Universities should also establish comprehensive institutional policies governing the ethical use of artificial intelligence, academic integrity, and algorithmic accountability in teaching, assessment, and administrative decision-making.

Finally, future implementation of NEP 2020 should continue to promote inclusive access, multidisciplinary learning, learner mobility, and international engagement while preserving India's constitutional identity, democratic values, and commitment to social justice. Sustained constitutional review of emerging regulatory reforms will remain essential to ensuring that higher education modernization advances both educational excellence and constitutional governance.

XI. CONCLUSION

The NEP 2020 represents a constitutional inflection point in India's higher education governance by marking a transition from fragmented regulatory control towards a more accountable, learner-centred, and constitutionally informed governance framework. Through the progressive implementation of regulatory reforms, the policy operationalizes the constitutional principles of substantive equality, cooperative federalism, institutional autonomy, constitutional morality, and responsible global engagement, thereby reshaping the normative foundations of higher education governance.

The foregoing constitutional, jurisprudential, and comparative analysis indicates that the transformative potential of the NEP 2020 ultimately depends upon the integrity of its implementation. Constitutional challenges relating to regulatory centralization, fiscal disparities among States, digital inequality, institutional capacity, and responsible data governance continue to influence the realization of its objectives. Addressing these challenges requires sustained federal cooperation, procedural fairness, institutional accountability, meaningful participation of the States, and governance mechanisms that remain responsive to technological and societal change.

Accordingly, NEP 2020 should be understood as an evolving constitutional project rather than a completed regulatory reform. Its long-term legitimacy will depend upon preserving constitutional values while adapting to emerging developments in digital governance, artificial intelligence, responsible data governance, academic freedom, and algorithmic accountability. Ultimately, the constitutional success of NEP 2020 will be measured not only by the modernization of university education regulation but also by its continuing fidelity to the constitutional principles of justice, equality, dignity, transparency, accountability, institutional autonomy, cooperative federalism, and the rule of law within an increasingly digital and globally interconnected post-secondary education system.

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Emerging New Technologies in Construction and Management

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***Abstract*—The immense impact made by innovative technologies has been realized in numerous industries globally. The construction industry is, without doubt, lagging concerning the utilization of technologies. Therefore, the study tries to explore different emerging technologies in the construction industry, with the identification of challenges and strategies by different stakeholders in its use.**

The study will used a pragmatism research philosophy together with a qualitative research strategy in determining emerging technologies in the construction industry while noticing stakeholder challenges and strategies. The analysis will be done with descriptive statistics using mean score ranking and a one-sample t-test. Findings - Each emerging technology challenge will analysed and compared to see how pressing the challenges were as well as the aligned strategies. A key indication of the study is that the familiarity of the various emerging technologies was based on how many occasions one had an encounter with the technology. Practical implications - The discussion's findings contribute to a better knowledge to construction stakeholders on the challenges and strategies for rising technology adoption and implementation competencies. Originality/value - The study reckoned stakeholders' challenges on the emerging technologies in the construction industry context and recommended strategies to balloon the adoption of these emerging technologies in a developing country setting.

***Index Terms*—Emerging Technologies, Construction Management, Technology**

I. INTRODUCTION

Technology keeps changing our lives all the time. Earlier, construction managers used paper files and manual methods to manage workers, costs, and project schedules. Most work was done by hand, which took more time and effort. Slowly, new tools like power tools and heavy machines were introduced. These helped workers complete tasks faster and made construction sites safer.

The construction industry was once known for being slow in using new technology. However, this has changed in recent years. Today, construction managers use both technology and traditional construction knowledge. Big construction companies started using new technologies earlier, and now many others are also adopting them. This is the best time for the construction industry to use modern technology.

In the last ten years, the construction field has grown very quickly. Many construction companies now use cloud-based software for project management and data analysis. These tools help in planning, monitoring, and controlling projects more effectively. Technology allows managers and workers to get real-time information from the site, which helps them take quick and better decisions. As a result, construction projects are completed more efficiently and with better quality.

II. AIM

The aim of this research is to understand how new and emerging technologies are being used in the construction industry and how they help improve work efficiency, safety, and project management.

III. OBJECTIVE

- To study different emerging technologies used in the construction industry.
- To understand how these technologies improve construction work, safety, and productivity.
- To identify the benefits of using modern technology in construction projects.
- To understand the challenges faced while adopting new technologies in construction.

IV. RESEARCH METHODOLOGY

This research is based on a descriptive and qualitative research approach. The study mainly uses secondary data to understand the role and impact of emerging technologies in the construction industry.

The data for this research is collected from existing sources such as:

- Research papers and journals
- Published articles and reports
- Books related to construction technology
- Trusted websites and industry reports

V. LITERATURE REVIEW

A literature review method is used to study various emerging technologies such as Artificial Intelligence (AI), Building Information Modelling (BIM), drones, Internet of Things (IoT), 3D

printing, robotics, blockchain, cloud computing, and virtual reality, and their applications in the construction industry.

a) Artificial Intelligence (AI)

Artificial Intelligence is making construction work safer, faster, and more efficient. It is used for project planning, scheduling, and resource management, which helps reduce time and cost. Machine Learning enables systems to learn from data and support better decision-making. AI also improves site safety, reduces errors, and speeds up project completion. Generative AI helps architects and engineers create better designs, use materials wisely, and plan sustainable projects.

b) Robotic Automation

Robotic automation is changing construction sites by using robots for tasks such as bricklaying, material handling, demolition, and 3D printing. Robots reduce manual labour, lower the risk of injuries, and increase work speed and accuracy. Automation also helps overcome labour shortages by handling repetitive tasks. Although costly, robotics improves productivity, safety, and efficiency and will play an important role in the future of construction.

c) Drones

Drones, also called unmanned aerial vehicles (UAVs), are widely used on construction sites today. They help in site surveying, inspection, and monitoring by capturing aerial photos and videos. Drones allow managers to track progress, create maps, and inspect hard-to-reach areas like tall buildings and bridges safely. They improve safety by reducing the need for workers to climb dangerous heights and make data collection faster and more accurate.

d) Internet of Things (IoT)

The Internet of Things (IoT) connects machines, tools, and materials on construction sites through sensors and smart devices. These devices provide real-time information about performance, safety, and usage. IoT helps improve site management, efficiency, and safety. It also supports the development of smart buildings that offer better comfort and a more personalized experience for users.

e) 3D Printing

3D printing is becoming an important technology in the construction industry, especially for printing concrete structures. It allows buildings to be made faster and in different shapes using materials like concrete and composites. 3D printing reduces labour and material waste by producing components directly on-site. Although large 3D printers are expensive, this technology saves time, lowers costs, and supports creative and customized building designs.

f) Blockchain

Blockchain is a digital system that securely records all project data and transactions in the form of connected records. In construction, it helps track costs, materials, and project progress accurately.

Blockchain improves transparency, reduces errors, and increases data security. Its decentralized nature makes it reliable and useful for managing construction projects of any size.

g) Cybersecurity

As construction work becomes more digital, protecting data has become very important. Cybersecurity helps keep project information, designs, and systems safe from cyber threats. Construction companies now use strong security measures like data encryption and threat detection to protect sensitive information and ensure smooth project operations.

h) Building Information Modelling (BIM)

Building Information Modelling (BIM) is a modern technology that improves accuracy and coordination in construction projects. It allows architects, engineers, and contractors to work together on a single digital model of a building. BIM helps reduce errors, improve planning, and solve design problems early. It also makes information sharing easier and has been successfully used in major projects like the Shanghai Tower.

i) Cloud Technology

Cloud technology allows construction companies to store large amounts of data online and access it anytime from anywhere. It helps project managers share information quickly and keep data secure in one place. Cloud-based tools improve coordination between different teams and make collaboration easier, especially on large construction projects.

Benefits of Emerging new Technologies

Emerging technologies are helping the construction industry reduce delays, control costs, solve labour shortages, and improve safety.

These technologies increase efficiency and productivity throughout the construction process.

- Automation: Technology automates tasks like payroll and calculations, reducing errors and saving time. Workers are paid correctly and on time.
- Increased Productivity: Software automates routine work, helping projects finish faster.
- Attracting New Talent: Technologies like AI, robotics, and 3D printing make construction jobs more attractive to young, tech-skilled workers.
- Higher Efficiency: Modern tools reduce manual work and allow workers to focus on skilled tasks.
- Self-Healing Concrete: Special concrete can repair small cracks on its own, making roads and bridges last longer.
- Better Collaboration: Digital platforms store all project information in one place, improving teamwork.
- Cost Savings: AI helps predict costs and reduce waste, improving budget control.
- Real-Time Data: Technology provides live information on project progress and worker performance, helping managers make better decisions.

- Improved Safety: Modern construction technologies improve site safety by reducing risks and preventing accidents.

Challenges faced by Stakeholders

- High Costs: While new technologies reduce labour and injury costs, they are expensive to buy and maintain. Costs include software, equipment, skilled workers, training, and regular updates. For example, 3D printers are costly and require continuous monitoring and maintenance.
- Interoperability Issues: Different systems like BIM, AR, and VR often do not work well together, making data sharing and updates difficult.
- Cloud Access Problems: Cloud-based tools need a strong and continuous internet connection. Poor network connectivity on construction sites limits the effective use of cloud technology.
- Resistance to Change: Many construction professionals are slow to accept new technologies, which reduces productivity and delays adoption.
- Privacy and Data Security: As more data is stored digitally, protecting client and project information has become a major concern.
- Collaboration Issues: Even with advanced tools, proper coordination between teams remains difficult without proper training and systems.
- Sustainability Concerns: Using eco-friendly materials and energy-efficient methods is challenging due to high costs and limited awareness.
- Labor Shortages: Lack of skilled workers increases the need for technology, but training workers to use new tools takes time and effort.

VI. RESULT

The study shows that emerging technologies are significantly transforming the construction industry. The findings indicate that technologies such as Artificial Intelligence (AI), robotics, drones, BIM, IoT, 3D printing, blockchain, and cloud computing are improving project planning, execution, and management.

The results reveal that:

- The use of AI and automation has improved project scheduling, reduced errors, and increased overall efficiency.
- Drones and IoT have enhanced site monitoring, safety inspections, and real-time data collection.
- BIM and cloud technology have improved collaboration among architects, engineers, and contractors by allowing them to work on a shared digital platform.
- 3D printing has reduced construction time, material waste, and labor dependency.
- Robotics and wearables have improved worker safety and productivity.
- Blockchain and cybersecurity tools have increased data transparency, security, and trust in construction transactions.

Overall, the adoption of these technologies has resulted in better productivity, improved safety, cost savings, and faster project completion across construction projects.

VII. DISCUSSION

The discussion highlights that while the benefits of emerging technologies are clear, their adoption is not without challenges. High initial costs, lack of skilled workers, resistance to change, and technical integration issues slow down widespread implementation. Poor internet connectivity also affects the effective use of cloud-based systems.

However, the long-term advantages outweigh these challenges. As professionals become more technology-friendly and training improves, adoption rates are expected to rise. The study confirms that emerging technologies play a crucial role in making construction smarter, safer, and more sustainable.

VIII. CONCLUSION

The idea that the construction industry is slow in adopting technology is no longer true. Modern technologies have improved the role of construction managers and made projects more efficient, safe, and productive. By using new technologies, construction companies can save time and money, reduce waste, and achieve better project results.

Although some technologies are still developing, they have great potential to change the future of construction. Technology and innovation will continue to play a major role in how buildings are designed and constructed.

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Khawf The Protector and the Tormentor in Zoulfa Katouh's as Long as the Lemon Trees Grow

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***Abstract*—This paper examines Zoulfa Katouh's young adult novel, As Long as the Lemon Trees Grow, through the theoretical lens of Trauma literature, analysing how the novel represents the psychological and physical well-being of the Syrian Revolution survivors. The novel centers on Salama kassab a young pharmacy student in Homs experiencing severe Post-Traumatic Stress Disorder (PTSD) and grief. The study explores how intense trauma disrupts traditional narrative structures, expressing internal suffering through sensory experiences, psychological detachment, and visual hallucinations. Drawing upon trauma theories formulated by Cathy Caruth and Judith Herman, this paper emphasizes the role of khawf, Salama's physical fear and trauma, which, beyond being a clinical symptom, serves as a crucial narrative device and coping mechanism. Khawf externalizes guilt, protects Salama from an overwhelming reality, and sustains her survival.**

***Index Terms*—Trauma literature, Khawf, Zoulfa Katouh, Survival, As Long as the Lemon Tree Grow, Syrian revolution**

I. INTRODUCTION

The horrifying realities of displacement, grief, and physical destruction are often portrayed in literature that has emerged from the Syrian conflict. Zoulfa Katouh shifts the emphasis inward in As Long as the Lemon Trees Grow, exploring the unseen psychological challenges brought on by conflict. Khawf, a striking representation of Salama's Post-Traumatic Stress Disorder (PTSD), is essential to her path. Despite Khawf's initial appearance as a tormentor who instils survivor's guilt, a closer examination reveals a deeply complex psychological contradiction: he is both a cause of pain and an essential self-preservation mechanism. This essay examines Khawf's dual function as an oppressor and protector using trauma theory.

The psychological devastation of war often cannot be expressed in traditional narrative forms, calling for new forms of literary representation of the unrepresentable. In As Long as the Lemon Trees Grow, Zoulfa Katouh addresses this challenge by giving tangible form to the invisible scars of post-traumatic stress disorder (PTSD). Through the personification of fear in the character of Khawf, Katouh links clinical reality to literary symbolism. Trauma in the story is not an atmospheric abstraction, but rather a dynamic that shapes the protagonist's quotidian choices, emotional boundaries, and survival strategies.

Ultimately, this paper illustrates how Katouh employs Khawf to externalize the internal cracks created by war trauma, indicating that in the face of overwhelming terror, the mind constructs its own radical ways of survival.

II. NARRATIVE CONTEXT AND HISTORICAL REALITIES

The initial uprising of the Syrian Revolution occurred in March 2011 as a consequence of the Arab Spring, which reached Syria after similar explosions of protests in Tunisia, Egypt, Libya, and Yemen. Initially, Syria appeared to stand on the sidelines, leading many observers to believe the regional upheaval would bypass the country. However, after Friday prayers on March 18, 2011, anti-regime protests broke out in several cities, most notably in Daraa, Hama, and Banyas. What started as a peaceful call for reform quickly escalated into a catastrophic civil conflict that reshaped the nation's socio-political landscape.

The setting of Homs plays a crucial role in reflecting Salama's psychological state. As one of the primary epicenters of the Syrian Revolution, Homs was heavily shelled and besieged, turning a thriving cultural center into a site of physical destruction. The hospital becomes a microcosm of the wider savagery of the war for an eighteen-year-old pharmacy student forced into the position of a surgeon. Salama experiences high stress daily due to the large number of wounded, the scarcity of medical supplies, and the ongoing threat of bombardment. This continuous physical siege is a clear reflection of Salama's psychological state; just as the city of Homs is under military siege, Khawf's phantom intrusion, anguish, and guilt are blocking Salama's consciousness.

Literary responses to such conflicts frequently struggle to find the right language for deep human suffering. In contemporary Middle Eastern novels, war is not merely a static background; it actively alters how characters think and disrupts conventional narratives.

As Long as the Lemon Trees Grow, written by Zoulfa Katouh in 2022, delves straight into this conflict. As a Syrian author who was raised in the diaspora, Katouh created the book to present a genuine, human perspective on the revolution that goes beyond the headlines and to give voice to the unstated trauma of the Syrian people. The narrative centers on eighteen-year-old Salama Kassab, a pharmacy student who, after losing her entire family, is compelled to work as a doctor at a besieged hospital in Homs.

III. KHAWF THROUGH THE LENS OF TRAUMA THEORY

To analyse Salama's experience, one must turn to the foundational framework of Trauma Literature. According to American literary critic Cathy Caruth trauma is not a simple event that happens at a specific moment, but an experience that is not fully grasped when it occurs, arriving belatedly in repetitive nightmares and flashbacks. Caruth states that it is "too soon, too unexpectedly, to be fully known and is therefore not available to consciousness until it imposes itself again, repeatedly…" (4). In Katouh's novel, trauma takes a personified, extraordinary form: khawf, a visible hallucination of fear personified as a ghostly man visible only to Salama. Katouh directly establishes Khawf as an internal psychological response, noting that Salama's internal monologue: "The horror I see isn't confined to the hospital. My terror has mutated in my mind, bestowed with a life and voice that never fails to show up each night." (14)

Cathy Caruth's theoretical framework on trauma rests mainly on the notion of the Unclaimed Experience, wherein an overpowering incident cannot be fully absorbed into awareness at the moment of its occurrence. Caruth says that the traumatic incident returns belatedly, assaulting the survivor's psyche through involuntary intrusive recollections and sensory disturbances. In Salama's situation, the tragedy of losing her mother, father, and brother, along with the daily atrocities in the hospital, exceeds her immediate cognitive processing capacity. Khawf thus appears as the actual personification of this belatedness. He operates as a continuous, lingering ghost of the unintegrated past, repeatedly pushing Salama to confront the horrors she attempted to suppress. By visualising her trauma as a corporeal figure who speaks and reacts, Katouh dramatizes Caruth's thesis, illustrating how trauma refuses to remain buried in the subconscious.

In Katouh's novel, Khawf is not merely a villainous presence, but a psychological manifestation of PTSD, a radical coping mechanism triggered by extreme trauma. By subjecting Salama to continuous psychological torture, he weaponizes her deepest fears to erode her emotional resilience. This suffering is evident early in the narrative, as Salama describes how Khawf's voice serves as a constant, sensory-based reminder of her omnipresent psychological suffering, noting: "His voice reminds me of the freezing water I splash over myself when I come home drenched in the martyrs' blood. It's stones weighing on my chest, sinking me to the earth below."(14)

Crucially, this intense psychological suffering brought on by trauma serves as an adaptive coping strategy rather than shattering Salama's psyche. According to Judith Herman's well-known notion of hypervigilance, which is discussed in her book Trauma and Recovery, Khawf is the result of a survivor's inner sense of security being damaged. Khawf provides Salama with mental support rather than lethal indifference. Even though Khawf is an absolute villain in her terror dreams, all of these hallucinations serve a practical purpose by preventing emotional stagnation.

IV. THE LEMON TREE AS A SYMBOL OF HOPE

Salama's psychological landscape is dominated by Khawf, but Katouh contrasts this haunting fear with potent emblems of human connection and resilience. The central motif of the lemon trees represents continuity, deep-rooted Syrian identity, and the lingering hope of renewal despite

widespread destruction. The lemon trees bind Salama to her roots and a future worth living for, while Khawf captures the oppressive weight of the immediate present and previous grief. Furthermore, Salama's interactions with Layla and Kenan speed up her slow mending process. Genuine human interaction enables Salama to ground herself in reality while Khawf uses shared shame to maintain separation. Her need for Khawf as a protective illusion gradually wanes as her emotional ties grow, supporting Herman's claim that trauma rehabilitation is ultimately mediated through safety and relational reconnection.

V. CONCLUSION

Ultimately, Katouh presents Khawf not as a malevolent entity that needs to be defeated but rather as an extreme psychological defence system. By his relentless horror, he paradoxically preserves Salama's physical life and sanity in a world of total destruction, proving that even her darkest hallucinations are intended to guarantee her survival.

Furthermore, Katouh's depiction of Khawf changes the way that trauma-induced hallucinations are interpreted in modern literature. Instead of viewing psychological anguish as merely a crippling symptom, the story highlights the mind's extraordinary ability to protect itself in times of acute danger. The book shows how the psyche can use fear as a weapon to preserve hope, agency, and an unwavering will to life in spite of external destruction by transforming internal suffering into a physical protector.

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The Impact of AI-Assisted Financial Advice on Investment Decision Quality among Young Investors: Evidence from Coimbatore District

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***Abstract*—The rapid advancement of Artificial Intelligence (AI) has transformed the financial services industry by providing investors with AI-assisted financial advisory tools, including robo-advisors, predictive analytics, personalized investment recommendations, and intelligent portfolio management systems. These technologies have the potential to improve investment decision-making by enhancing access to financial information, reducing behavioral biases, and supporting data-driven investment strategies. However, empirical evidence on the effectiveness of AI-assisted financial advice among young investors in India remains limited, particularly in the context of emerging financial markets such as Coimbatore District. This study aims to examine the impact of AI-assisted financial advice on the investment decision quality of young investors. Specifically, it investigates the influence of AI-based financial advice on investment decision quality and explores the role of financial literacy, trust in AI, and perceived usefulness in shaping investment behavior. A descriptive and analytical research design will be adopted using primary data collected through a structured questionnaire from young investors aged 18–35 years in Coimbatore District. The data will be analyzed using descriptive statistics, reliability analysis, correlation, multiple regression, and Structural Equation Modelling (SEM) to validate the proposed conceptual framework. The findings are expected to provide valuable insights into the effectiveness of AI-driven financial advisory services in improving investment outcomes and promoting informed financial decision-making. The study will contribute to the growing literature on behavioral finance and financial technology (FinTech) while offering practical implications for financial institutions, fintech companies, policymakers, and investors seeking to leverage AI for better investment decisions.**

***Index Terms*—Artificial Intelligence, AI-Assisted Financial Advice, Investment Decision Quality, Young Investors, Financial Literacy, Behavioral Finance.**

I. INTRODUCTION

Artificial Intelligence (AI) has emerged as a transformative technology in the financial services sector, reshaping the way individuals make investment decisions. AI-assisted financial advisory tools, such as robo-advisors, machine learning algorithms, predictive analytics, and personalized investment platforms, provide investors with real-time market insights, risk assessment, and customized investment recommendations. These innovations enable investors to make faster, more informed, and data-driven financial decisions while reducing the influence of human errors and behavioural biases.

Young investors, particularly those between the ages of 18 and 35, are increasingly adopting digital financial platforms due to their familiarity with technology and growing interest in wealth creation. However, despite easy access to financial information, many young investors lack adequate financial knowledge and often make investment decisions based on emotions, peer influence, or incomplete information. AI-assisted financial advice has the potential to bridge this gap by offering objective, timely, and personalized guidance that can enhance investment decision quality.

Coimbatore District has witnessed significant growth in digital banking, fintech adoption, and online investment activities, making it an appropriate setting for examining the effectiveness of AI-assisted financial advisory services. Despite the rapid expansion of AI applications in finance, limited empirical research has explored their impact on the investment decision quality of young investors at the regional level in India.Against this background, the present study aims to examine the impact of AI-assisted financial advice on investment decision quality among young investors in Coimbatore District. The findings are expected to contribute to the fields of Behavioural Finance and Financial Technology (FinTech) by providing insights for investors, financial institutions, fintech companies, and policymakers on promoting AI-enabled investment practices and improving financial decision-making.

II. OBJECTIVES OF THE STUDY

1. To examine the level of adoption of AI-based financial assistance among young investors in Coimbatore District.
2. To analyse the impact of AI-based financial assistance on the investment decision quality of young investors.
3. To evaluate the relationship between financial literacy and investment decision quality among young investors.
4. To assess the mediating role of trust in AI in the relationship between AI-based financial assistance and investment decision quality.

III. REVIEW OF LITERATURE

1. Belanche et al. (2019) examined the adoption of robo-advisory services and found that perceived usefulness, ease of use, and trust significantly influence investors' willingness to

adopt AI-based financial advisory platforms. The study concluded that AI improves investment efficiency by providing personalized and data-driven recommendations.

2. Jabeur et al. (2022) investigated the role of Artificial Intelligence in investment decision-making and reported that AI-powered financial tools enhance portfolio performance by reducing human bias and improving the accuracy of investment decisions. The study emphasized AI as an effective decision-support system for investors.
3. Kumar and Goyal (2015) explored behavioural biases affecting individual investors in India and found that overconfidence, herding, and loss aversion significantly influence investment decisions. The authors suggested that technology-driven financial advice can help mitigate these biases and improve investment outcomes.
4. OECD (2023) highlighted that financial literacy is a key determinant of effective investment decision-making. The report emphasized that digital financial technologies, including AI-assisted advisory services, can improve investors' financial knowledge and promote informed investment behaviour.

IV. RESEARCH GAP

Most existing studies focus on the adoption of AI and robo-advisory services or on behavioural biases in investment decisions. However, limited research has examined how AI-assisted financial advice directly influences the investment decision quality of young investors, particularly in the context of Coimbatore District. Therefore, the present study seeks to bridge this gap by analysing the impact of AI-assisted financial advice on investment decision quality among young investors.

V. THEORETICAL FRAMEWORK

The Technology Acceptance Model (TAM) explains that an individual's intention to use AI-assisted financial advisory services is influenced by Perceived Usefulness (PU) and Perceived Ease of Use (PEOU). When young investors perceive AI tools as useful, reliable, and easy to use, they are more likely to adopt them for investment decisions.

Behavioural Finance Theory suggests that investors often make irrational decisions due to behavioural biases such as overconfidence, herding, and loss aversion. AI-assisted financial advice can reduce these biases by providing objective, data-driven, and personalized investment recommendations, thereby improving the quality of investment decisions. Based on these theories, the study proposes that AI-Assisted Financial Advice (independent variable) positively influences Investment Decision Quality (dependent variable). Financial Literacy, Trust in AI, and Perceived Usefulness may further strengthen this relationship.

AI based Financial Assistance

AI-Based Financial Assistance refers to the use of Artificial Intelligence technologies such as machine learning, robo-advisors, chatbots, predictive analytics, and personalized financial recommendation systems to support individuals in managing their finances. These AI-powered

tools help users with budgeting, investment planning, risk assessment, portfolio management, savings, debt management, and financial decision-making by providing real-time, personalized, and data-driven insights.

Investment Decision Quality among Young Investors

Investment Decision Quality refers to the extent to which young investors make rational, informed, and effective investment decisions that align with their financial goals, risk tolerance, and market conditions. High-quality investment decisions are based on accurate financial information, systematic analysis, and appropriate risk assessment rather than emotions or behavioural biases.

Dimensions (Indicators)

The construct can be measured using the following dimensions:

1. Information-Based Decision Making – Using reliable financial information before investing.
2. Risk Assessment – Evaluating investment risks before making decisions.
3. Return Evaluation – Comparing expected returns with associated risks.
4. Investment Confidence – Confidence in making investment decisions.
5. Decision Effectiveness – Satisfaction with investment outcomes and achievement of financial objectives.
6. Behavioural Control – Ability to avoid emotional or impulsive investment decisions.

VI. DATA ANALYSIS AND INTERPRETATION

Table 1: Mean Scores of AI-Based Financial Assistance and Investment Decision Quality by Age

Age Group (Years)	No. of Respondents (n)	Mean Score	Standard Deviation
20–25	45	4.28	0.51
25–30	60	4.11	0.58
30–35	40	3.89	0.63
Above 40	25	3.65	0.70
Total	170	4.03	0.61

Table 2: One-Way ANOVA

Source of Variation	Sum of Squares	df	Mean Square	F	Sig. (p)
Between groups	5.82	3	1.94	5.48	0.001
Within group	58.64	166	0.35		
Total	64.46	169			

Interpretation: The One-Way ANOVA results indicate a statistically significant difference in investment decision quality across different age groups ($F = 5.48$, $p = 0.001$). The 20–25 years age group recorded the highest mean score (4.28), indicating that younger investors are more likely to use AI-based financial assistance effectively in making investment decisions. In contrast, respondents above 40 years had the lowest mean score (3.65), suggesting comparatively lower reliance on AI-assisted financial tools. This finding implies that age influences the effectiveness and adoption of AI-based financial assistance, with younger investors demonstrating better investment decision quality through greater acceptance of AI technologies.

Conclusion: Since $p < 0.05$, the difference among age groups is statistically significant. Therefore, age has a significant influence on the impact of AI-based financial assistance on investment decision quality.

VII. FINDINGS AND SUGGESTIONS

Findings

- The majority of respondents in the 20–30 years age group frequently use AI-based financial assistance tools such as robo-advisors, investment apps, and AI-enabled financial recommendations.
- Young investors perceive AI-based financial assistance as useful, time-saving, and capable of providing personalized investment guidance.
- Trust in AI significantly influences the adoption of AI-based financial assistance and strengthens its impact on investment decision quality.
- One-way ANOVA results indicate that the impact of AI-based financial assistance varies across age groups, with younger investors showing higher acceptance and better investment outcomes than older respondents.

Suggestions

- Financial institutions and fintech companies should develop user-friendly and transparent AI-based financial assistance platforms.
- Investor education programs should be conducted to improve financial literacy and awareness of AI-assisted investment tools.
- Young investors should use AI-based financial assistance as a decision-support tool rather than relying solely on automated recommendations.
- Future studies may include larger samples and compare urban and rural investors or different regions of India.

ACKNOWLEDGMENT

This study examined the impact of AI-based financial assistance on the investment decision quality of young investors in Coimbatore District. The findings reveal that AI-based financial assistance positively influences investment decision quality by providing timely, personalized, and data-

driven financial guidance. Financial literacy and trust in AI play an important role in enhancing the effectiveness of these tools. Younger investors, particularly those between 20 and 30 years, show greater adoption of AI-based financial assistance and better investment decision outcomes. The study contributes to the growing literature on Behavioural Finance and Financial Technology (FinTech) by demonstrating that AI can improve investment decision-making when combined with adequate financial knowledge and user trust. The results have practical implications for investors, financial institutions, fintech companies, and policymakers in promoting responsible and effective use of AI in personal finance and investment management. Overall, AI-based financial assistance has the potential to become an important tool for improving the quality of investment decisions among the emerging generation of digital investors.

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Analysis of Uganda's Political Governance Paradigm and Economic Transformation Evidence from National Resistance Movement Regime

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***Abstract*—This article evaluates Uganda's political governance paradigm and economic transformation under the National Resistance Movement (NRM) regime since 1986. It examines the relationship between political stability, governance reforms, and socio-economic development, assessing the extent to which the NRM's policy framework has shaped Uganda's development trajectory. The study adopted a singular mixed methodology that enabled collection of the qualitative analysis of policy documents, government reports. The study used interviews, survey, focused group discussion methods that enabled the study explores developments in governance, agricultural modernization, infrastructure expansion, and economic growth. The findings suggest that the NRM regime has played a significant role in restoring political stability and facilitating economic recovery following decades of political turmoil and economic decline. Notable achievements include increased agricultural productivity, expansion of infrastructure, growth in export earnings, improvements in service delivery, and enhanced regional economic integration. The transformation of the dairy sector, alongside broader agricultural and private-sector development, illustrates the impact of state-led development initiatives on economic performance. However, the study also identifies enduring challenges, including corruption, youth unemployment, regional inequalities, public debt, and concerns regarding democratic accountability, political pluralism, and institutional effectiveness. The article argues that Uganda's experience demonstrates the centrality of political stability in fostering economic transformation, while also highlighting the limitations of development gains in the absence of stronger governance institutions and inclusive political processes. By providing a balanced assessment of Uganda's post-1986 development experience, the study contributes to broader debates on governance, state capacity, and economic transformation in Uganda and entire contemporary Africa.**

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***Index Terms*—Economic Transformation, Governance, Agricultural Development, Dairy Industry, Political Stability, Economic Growth, Development Policy**

I. INTRODUCTION

The nexus between political governance and economic transformation has attracted considerable scholarly attention, particularly in developing countries where political institutions significantly influence development outcomes (Mohamad, 2024). In Africa, debates on governance and development have increasingly focused on the extent to which political stability, state capacity, and institutional reforms contribute to sustainable socio-economic transformation (Gumede et al., 2026a). Uganda presents an important case for examining these dynamics because of its remarkable transition from a period of political instability. It is notable that, economic decline in the 1970s and early 1980s to a relatively stable political environment and expanding economy under the National Resistance Movement (NRM) regime since 1986.

Since assuming power in 1986, the NRM government has pursued a broad agenda of political reconstruction and economic reform aimed at restoring peace, rebuilding state institutions, revitalizing agricultural production, expanding infrastructure, and promoting private-sector-led growth (Dept, 2024). These interventions have generated notable outcomes, including increased agricultural productivity, growth in export earnings, improved infrastructure, expansion of social services, and sustained economic growth. For instance, Uganda's dairy sector has transformed from a largely subsistence activity into a significant contributor to national income and export earnings. While investments in roads, energy, telecommunications, and regional integration have enhanced the country's economic competitiveness (Abor et al., 2025). These developments make Uganda a compelling case for evaluating the relationship between governance paradigms and economic transformation.

Despite extensive literature on Uganda's political economy, existing studies have largely examined political governance and economic transformation as separate phenomena. Much of the scholarship focuses either on democratic governance, political liberalization, and institutional reforms or on economic growth, poverty reduction, and sectoral development (Boadu-Ayeboafoh, 2006). Consequently, limited attention has been paid to the interaction between Uganda's governance paradigm and the broader processes of economic transformation over the entire NRM period. Furthermore, existing analyses often emphasize either the successes or the shortcomings of the NRM regime, resulting in polarized interpretations that inadequately capture the complexity of Uganda's development experience (Van et al., 2025). This creates a significant knowledge gap regarding how governance structures, political stability, and policy choices have collectively shaped Uganda's socio-economic trajectory since 1986.

Motivated by the need to provide a more integrated and balanced assessment of Uganda's development experience, this study evaluates the political governance paradigm and economic transformation under the NRM regime. Specifically, the study seeks to: (i) examine the key characteristics of Uganda's political governance framework since 1986; (ii) assess the major dimensions of economic transformation achieved during the NRM era; (iii) analyze the relationship

between political governance and socio-economic development outcomes; and (iv) identify the persistent governance and development challenges that continue to affect Uganda's transformation agenda.

The study lies in its integrated analytical approach that bridges the governance and economic transformation literature within a single evaluative framework. Rather than treating political and economic developments as independent processes, the article demonstrates how governance institutions, political stability, policy implementation, and state capacity interact to influence economic transformation (Ghosh, 2023). By synthesizing evidence from governance reforms, agricultural modernization, infrastructure development, and economic performance, the study provides a comprehensive understanding of Uganda's post-1986 development trajectory. In doing so, it contributes to ongoing debates on governance, state-building, and development in Africa and offers policy insights relevant to countries pursuing long-term socio-economic transformation under conditions of political change (Fossum et al., 2023).

The article is structured as follows. The next section reviews the theoretical and empirical literature on political governance and economic transformation. This is followed by the methodology section, which outlines the research design and analytical approach. Subsequent sections examine Uganda's political governance paradigm and key dimensions of economic transformation under the NRM regime. The final section presents conclusions and policy implications.

II. METHODOLOGY

This study adopted mixed-methods to enable collection of both qualitative and quantitative data required for the study (Patrick, 2021). The method was suitable; it enabled effective exploration of the variables under investigation. The study also used a case research design grounded in a multiple case study approach. The integration of mixed-methods and research design enabled the comprehensive findings of the variables (Poth, 2023).

This study was supported by the pragmatism philosophy that enabled epistemology and ontological stance to ease the study. These approaches eased the collection of both quantitative and qualitative data to provide a comprehensive understanding of the paradox of livestock farming in Sub-Saharan Africa’s cattle corridor (Oyanedel et al., 2023). The case study design was appropriate because it allowed in-depth examination of livestock farming systems within real-life contexts across selected districts in Uganda.

III. RESEARCH DESIGN

This study adopted a mixed-methods case study design combining quantitative and qualitative approaches to evaluate Uganda’s political governance paradigm and economic transformation, with specific emphasis on the cattle corridor (Akotia et al., 2023), (Alan et al., 2021). This design was considered appropriate as it enables both statistical measurement of socio-economic trends and an

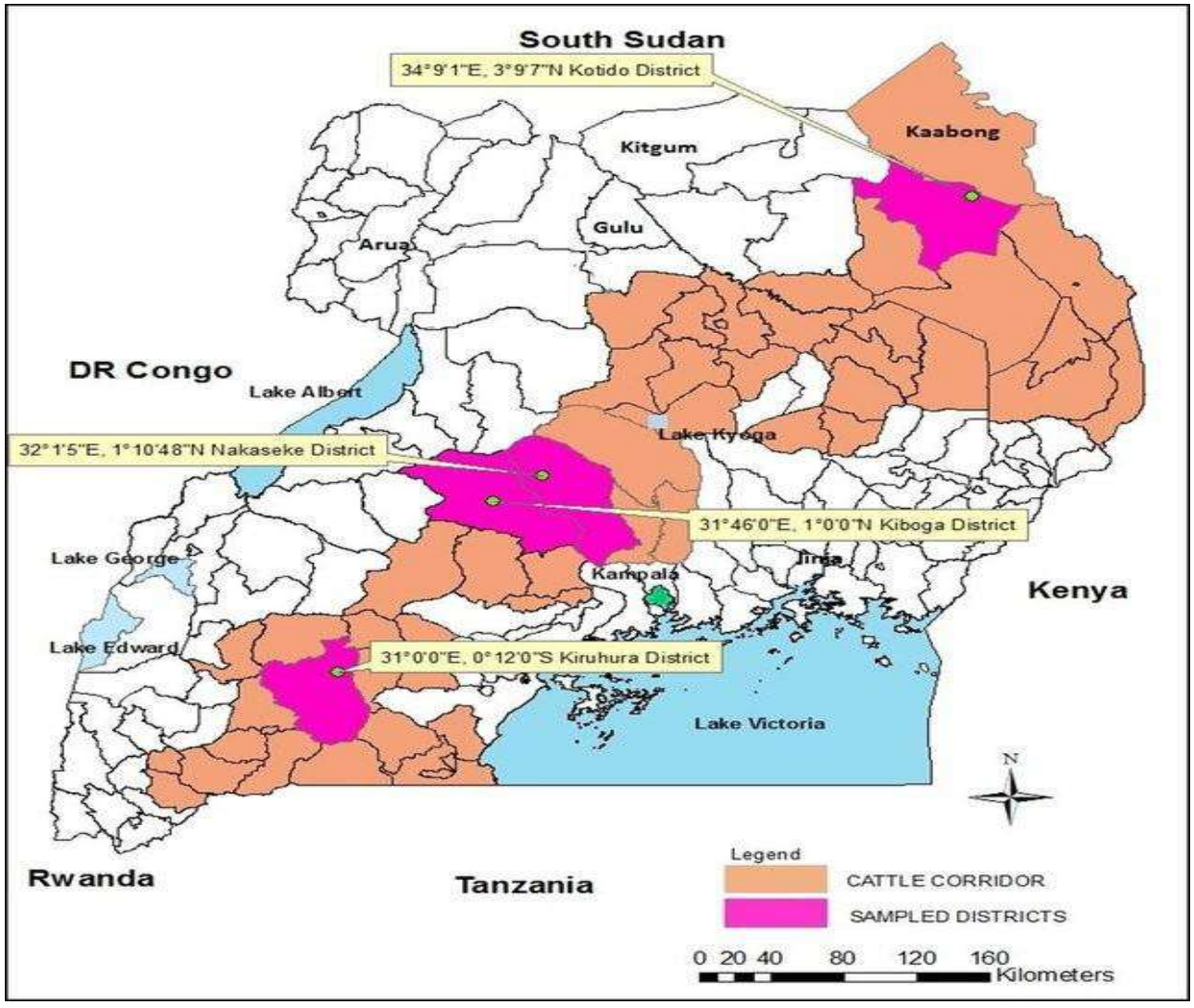
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in-depth exploration of community experiences under the National Resistance Movement (NRM) governance framework.

IV. STUDY AREA

The study was conducted in Uganda's cattle corridor, a major agro-ecological zone characterized by extensive livestock production and dairy farming systems (Ibeagha-Awemu et al., 2025), (Gaouar et al., 2026a). The region is central to Uganda's agricultural transformation agenda, particularly in relation to commercialization, productivity enhancement, and livestock-based livelihoods. However, it should be notable that, in order to achieve social economic transformation of people number, strategies must be embrace that entails education, health, peace and security. All these are drivers for socio-economic transformation of the country and the entire region (Kosmaczewska & Poczta, 2021).

A Map of Uganda indicating cattle corridor as study areas



(Source: Google maps retrieve 29th May, 2026)

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V. POPULATION AND SAMPLE SIZE

The target population comprised households engaged in livestock production, dairy farmers, cooperative members, and key stakeholders along the cattle value chain (Burkart et al., 2024). A scientifically determined sample of 4,600 respondents was selected from different communities within the cattle corridor to ensure representativeness and statistical reliability. These include Kirihura, Kibogga, Nakaseke and Kotido Districts in Uganda's cattle corridor strip.

VI. SAMPLING PROCEDURE

A multi-stage sampling technique was employed; these include Purposive, stratified, and simple random sampling system (Dale, 2026). First, districts within the cattle corridor were purposively selected based on their intensity of livestock production. Second, sub-counties and parishes were randomly selected. Finally, households were selected using systematic random sampling (Moreira et al., 2012). In addition, purposive sampling was used to select key informants, including veterinary officers, extension workers, local leaders, and cooperative managers.

VII. DATA COLLECTION METHODS

Primary data were collected using survey method in which structured questionnaires were developed, interviews, and focus group discussions (Poth, 2023). These data collection methods and instruments were generated quantitative data on livestock production, income levels, market access, and adoption of improved farming practices. Qualitative tools captured perceptions on governance, policy implementation, service delivery, and agricultural transformation.

VIII. DATA ANALYSIS

Quantitative data were analyzed using descriptive and inferential statistical techniques, including frequencies, percentages, and cross-tabulations to examine patterns in livestock production and economic outcomes (Badr & Lhoussaine, 2024). Qualitative data were analyzed thematically to identify recurring patterns related to governance influence, agricultural modernization, productivity changes, and development constraints. Findings from both strands were integrated during interpretation to enhance analytical depth.

IX. VALIDITY AND RELIABILITY

Validity was ensured through pre-testing of research instruments in selected communities within the cattle corridor. Reliability was strengthened through standardized data collection procedures, enumerator training, and consistency checks (Okoko, 2024). Triangulation of quantitative and qualitative data sources further enhanced the credibility of the findings.

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X. ETHICAL CONSIDERATIONS

Ethical clearance was obtained from relevant institutional authorities prior to data collection. Informed consent was obtained from all participants, and participation was voluntary. Confidentiality, anonymity, and data protection principles were strictly observed throughout the study (Ahmad & Islam, 2024).

XI. METHODOLOGICAL LIMITATIONS

The study acknowledges potential limitations, including recall bias among respondents and variations in socio-economic conditions across districts within the cattle corridor, which may affect generalizability (Anwar & Shima, 2025). However, the large sample size and mixed-methods approach significantly strengthen the robustness and reliability of the findings.

XII. RESULTS

Findings from the cattle corridor indicate that Uganda's economic transformation has been strongly shaped by state-led development strategies implemented under the National Resistance Movement (NRM) regime. The Government of Uganda has tried Key programs such as Entandikwa, National Agricultural Advisory Services (NAADS), Emyooga, the Parish Development Model (PDM), and broader wealth creation initiatives have been central in integrating rural households into the money economy (A. P. Jr & Sousa, 2023). These interventions reflect a deliberate policy shift toward decentralized development financing aimed at improving household income, productivity, and enterprise development at community level.

Respondents consistently indicated that the Parish Development Model, which allocates seed capital to parishes, has enhanced access to low-cost financing for household enterprises. Similarly, Emyooga and NAADS were perceived as important mechanisms for promoting skills development, enterprise formation, and agricultural modernization, particularly in livestock-based livelihoods (Resources, 2021). However, concerns were raised regarding uneven access, administrative inefficiencies, and limited financial absorption capacity in some communities.

XIII. AGRICULTURAL TRANSFORMATION IN THE CATTLE CORRIDOR

A major finding of the study is the structural transformation of livestock production systems from predominantly subsistence and nomadic grazing (okusetura) to more sedentary and commercialized dairy farming systems. Respondents highlighted increased adoption of improved cattle breeds, pasture development, and cattle -grazing practices as key drivers of productivity growth (M. R. Jr & Aiken, 2019).

XIV. CATTLE FARMING TO BOOST HOUSEHOLD INCOME



(Source: Field collection 29th May, 2026)

The introduction of dairy infrastructure, including milk cooling facilities, facilitated value addition and reduced post-harvest losses (Gaouar et al., 2026b). These changes contributed to increased household incomes and integration into regional and national dairy value chains. The transition from indigenous livestock systems to crossbreeding and commercial dairy farming was widely regarded as a turning point in the economic modernization of the cattle corridor (Panel, 2020).

XV. INFRASTRUCTURE DEVELOPMENT AND ENABLING ENVIRONMENT

The study findings indicate that economic transformation in the cattle corridor has been strongly supported by improvements in national infrastructure (Fitzsimons et al., 2024). Investments in road networks, energy systems, and regional transport corridors have enhanced market access and reduced transaction costs for agricultural producers.

Respondents emphasized that road connectivity linking rural production zones to urban and cross-border markets have facilitated the commercialization of livestock products. In addition, improvements in electricity generation and distribution have supported agro-processing, cold chain systems, and small-scale industrial activities (Crush et al., 2020). The development of railway and pipeline infrastructure was also identified as part of a broader strategy to shift freight transport away from roads, thereby improving efficiency in the logistics sector.

XVI. GOVERNANCE, PEACE, AND INSTITUTIONAL STABILITY

A key finding is that respondents widely associate economic transformation with political stability and security provided by state institutions, particularly the Uganda People's Defence Forces

(UPDF), police, and judiciary. Peace and law and order were consistently identified as foundational conditions for wealth creation and investment in rural areas (Gumede et al., 2026b).

The decentralization of governance and the presence of local administrative structures were also viewed as important in facilitating service delivery and implementation of development programs. However, concerns were raised regarding corruption, accountability gaps, and uneven enforcement of development policies, which in some cases limit the effectiveness of government programs (Bhattacharya et al., 2025).

XVII. ECONOMIC DIVERSIFICATION AND STRUCTURAL CHANGE

The findings further reveal a gradual shift from a predominantly agrarian subsistence economy to a more diversified economic structure encompassing commercial agriculture, manufacturing, services, and ICT (Agrawal et al., 2024). This diversification is reflected in the expansion of agro-processing industries, growth in export-oriented production, and increasing participation of households in non-farm economic activities.

Respondents noted that Uganda's economic strategy emphasizes value addition, industrialization, and knowledge-based sectors as key drivers of future growth. However, the persistence of low productivity in some agricultural subsectors and limited industrial absorption capacity remain structural constraints.

XVIII. CRITICAL PERSPECTIVES AND GOVERNANCE CHALLENGES

Despite reported achievements, the study identified critical concerns regarding implementation effectiveness, equity, and governance outcomes of development programs (Parsafar & Miller, 2024). Some respondents pointed to inefficiencies in fund distribution under programs such as PDM and Emyooga, as well as disparities in access to development resources across districts.

Additionally, issues of corruption, weak institutional coordination, and limited monitoring mechanisms were highlighted as factors undermining program effectiveness. These findings suggest that while the policy framework is comprehensive, governance and implementation challenges continue to affect development outcomes (A. P. Jr & Sousa, 2023).

Overall, the findings demonstrate that Uganda's cattle corridor has undergone significant socio-economic transformation driven by a combination of state-led development programs, infrastructure expansion, agricultural modernization, and relative political stability (Agrawal et al., 2024). However, the sustainability of these gains depends on addressing governance inefficiencies, strengthening institutional accountability, and improving equitable access to development resources.

The study therefore establishes that economic transformation in the cattle corridor is not solely a product of market forces but is deeply embedded in governance structures, policy interventions, and state capacity.

XIX. DISCUSSION

The findings of this study underscore the centrality of political governance in shaping Uganda's economic transformation, particularly within the cattle corridor where livestock production constitutes a key livelihood system (B, 2022). The evidence suggests that Uganda's development trajectory under the National Resistance Movement (NRM) regime is characterized by a deliberate state-led strategy combining political stability, decentralized service delivery, and targeted economic programs aimed at integrating rural households into the monetary economy (The Oxford Handbook of the Moroccan Economy, 2026).

A theoretical implication emerging from the study is the strong link between political stability and productive economic activity. Respondents consistently associated peace, security, and functioning legal institutions with increased investment in livestock production and agricultural commercialization (Moritz et al., 2026). This finding aligns with state-centric development perspectives which argue that effective governance institutions are a prerequisite for sustained economic transformation. The role of institutions such as the Uganda People's Defence Forces (UPDF), police, and judiciary was repeatedly emphasized as foundational in maintaining order and enabling rural economic participation (Zioło & Zaleska, 2025).

The study also highlights the significance of state-led development interventions such as the Parish Development Model (PDM), Emyooga, NAADS, and earlier Entandikwa initiatives in facilitating grassroots economic empowerment (Manyane & Mariam, 2023). These programs reflect a policy shift toward localized capital provision and household enterprise development. However, while these interventions have expanded financial inclusion and encouraged participation in income-generating activities, their effectiveness appears uneven across communities. This suggests that implementation capacity, governance quality, and local administrative efficiency significantly mediate development outcomes.

From an agricultural transformation perspective, the cattle corridor has experienced a gradual but notable shift from subsistence and nomadic livestock systems to more commercialized and sedentary production models (Amanullah, 2024). The adoption of improved breeds, pasture development, and zero-grazing practices indicates a structural change in livestock management. This transition has contributed to increased milk production, value addition, and integration into formal markets. Nevertheless, the persistence of traditional practices in some areas highlights the coexistence of modern and customary production systems, reflecting uneven modernization processes.

Infrastructure development emerges as another critical driver of transformation. Improvements in road networks, energy supply, and regional connectivity have reduced transaction costs and enhanced market access for agricultural producers (Akram, 2026). These investments have not only facilitated domestic trade but have also strengthened Uganda's integration into regional markets (Estudillo et al., 2022). However, infrastructural gains remain spatially uneven, with some rural areas still experiencing limited access to reliable transport and energy services, thereby constraining full economic integration.

The findings further reveal that Uganda's economic transformation strategy is increasingly anchored in a diversification agenda spanning commercial agriculture, manufacturing, services, and ICT (Agrawal et al., 2024). This structural shift is consistent with broader development theories that emphasize economic complexity and value addition as pathways to sustained growth. However, the continued dominance of primary production in rural areas suggests that structural transformation remains incomplete.

At the same time, the study identifies important governance and implementation challenges that temper the overall assessment of Uganda's development model. Issues such as corruption, uneven distribution of development funds, and limited institutional accountability were reported as constraints on the effectiveness of government programs (Aceska et al., 2025). These challenges highlight a persistent gap between policy design and implementation outcomes, suggesting that institutional capacity remains a critical bottleneck in Uganda's transformation agenda.
The study also engages with broader political economy debates concerning the role of the state in development (Ahluwalia, 2025). While some perspectives emphasize the effectiveness of Uganda's governance model in restoring stability and promoting growth, others caution that the sustainability of these gains depends on deeper institutional reforms and enhanced political accountability. The findings suggest a hybrid outcome: significant economic progress coexists with unresolved governance deficits (Ali et al., 2024).

In synthesis, Uganda's experience in the cattle corridor illustrates a development pathway driven by strong state intervention, infrastructural investment, and agricultural modernization, but constrained by uneven implementation and governance challenges (Estudillo et al., 2022). The evidence suggests that while the foundations for transformation have been established, the transition toward fully inclusive and sustainable development requires stronger institutional performance, improved accountability mechanisms, and more equitable distribution of development resources.

XX. CONCLUSION

This study evaluated Uganda's political governance paradigm and economic transformation under the National Resistance Movement (NRM) regime, with specific attention to developments in the cattle corridor. The evidence demonstrates that since 1986, Uganda has experienced substantial

political stabilization and significant socio-economic transformation driven by deliberate state-led development strategies, institutional reforms, and sustained investments in infrastructure and productive sectors.

Findings indicate that programs such as the Parish Development Model (PDM), Emyooga, NAADS, and earlier livelihood interventions have played an important role in expanding financial inclusion and promoting household participation in the money economy. In the cattle corridor, these interventions, combined with agricultural modernization—particularly the shift from nomadic livestock systems to commercialized dairy farming—have contributed to increased productivity, improved household incomes, and stronger integration into national and regional markets.

The study further establishes that infrastructure development, peace and security, and governance structures have been central enablers of economic transformation. Improvements in roads, energy systems, and institutional stability have reduced production constraints and facilitated market access, thereby strengthening Uganda's broader economic performance. However, the study also reveals persistent challenges, including uneven implementation of development programs, governance inefficiencies, corruption concerns, and disparities in access to development resources, which continue to constrain inclusive transformation.

Overall, the study concludes that Uganda's post-1986 development experience reflects a mixed but progressive transformation trajectory characterized by significant economic gains alongside structural and governance limitations. While the foundations for long-term transformation have been established, sustaining and deepening these gains will require stronger institutional accountability, improved policy implementation, and more equitable distribution of development resources.

The cattle corridor experience specifically demonstrates that rural transformation is achievable under conditions of political stability and targeted state intervention, but long-term sustainability depends on addressing remaining structural constraints and enhancing the productivity and inclusiveness of rural economies.

XXI. IMPLICATION OF THE STUDY

The findings of this study have important implications for understanding the relationship between political governance and economic transformation in Uganda. First, the evidence demonstrates that political stability and strong state institutions are foundational to rural economic development. The sustained role of security institutions, administrative structures, and decentralized governance systems suggests that development outcomes are closely tied to governance effectiveness and institutional coordination.

Second, the study highlights that state-led development programs such as the Parish Development Model (PDM), Emyooga, and NAADS play a significant role in expanding financial inclusion and promoting grassroots enterprise development. However, their uneven effectiveness implies that policy success depends not only on resource allocation but also on implementation capacity, accountability systems, and local governance efficiency.

Third, the findings reveal that structural transformation in Uganda remains incomplete, despite progress in agricultural modernization, infrastructure expansion, and sectoral diversification. This suggests that economic transformation is a gradual process that requires sustained investment in productivity enhancement, value addition, and industrial development.

Finally, the study implies that governance quality is a critical mediating factor between policy formulation and development outcomes. Without strong accountability mechanisms, the impact of otherwise well-designed programs may be diluted at the implementation level.

XXII. RECOMMENDATIONS

There is a need to reinforce transparency and accountability mechanisms in the implementation of development programs such as PDM and Emyooga. Strengthening oversight institutions at national and local levels will help reduce inefficiencies, corruption risks, and misallocation of resources.
The study recommends that the Local government structures should be equipped with adequate technical, financial, and human resources to effectively manage development programs. Capacity-building initiatives for district and parish-level administrators are essential to improve service delivery and program efficiency.
The study also recommended government of Uganda should intensify efforts to transition farmers from subsistence and semi-nomadic systems to fully commercialized and climate-smart agricultural production. This includes expanding access to improved breeds, irrigation systems, pasture development, veterinary services, and agro-processing facilities.
The study recommended to accelerate structural transformation, greater emphasis should be placed on agro-industrialization and value addition on national sustainable economic transformation. Investments in processing facilities, cold chain systems, and industrial parks will enhance competitiveness and increase export earnings from agricultural products.
Although programs such as PDM provide seed capital, there is still a need for broader access to affordable and sustainable credit systems. Strengthening microfinance institutions and cooperative savings structures can complement government interventions and support enterprise growth.
Furthermore, the study recommended for development interventions should be designed to ensure equitable distribution of resources across regions and socio-economic groups. Special attention should be given to vulnerable households, youth, and women to reduce inequality and enhance inclusive growth.

Lastly the study recommends for continued investment in transport, energy, and ICT infrastructure is essential to reduce production and transaction costs. Regional trade integration should also be deepened to expand market opportunities for Uganda's agricultural and industrial products.

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Operational Factors and Operational Productivity of Private Higher Education Institutions in Valencia City, Bukidnon

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***Abstract*—This study aimed to describe the level of operational factors of private higher education institutions in Valencia City, Bukidnon. Specifically, it seeks to answer in terms of technology adoption, resource management, and human resource practices, assess the level of operational productivity of private higher education institutions in terms of resource use and employee productivity, and examine the significant relationship between operational factors and operational productivity of private higher education institutions. Using a descriptive-correlational research design, one hundred respondents consisting of faculty and staff from private higher education institutions in Valencia City, Bukidnon, were selected through stratified sampling as respondents of the study and data were collected through a researcher-made instrument survey questionnaire. Statistical analyses, including mean, standard deviation, and Pearson Product Moment Correlation, were applied to measure the significant relationship between operational factors of private higher education institutions. The findings showed that technology adoption, resource management, and human resource practices all obtained high overall mean scores interpreted as Excellent Implementation, indicating favorable perceptions among respondents regarding institutional operational practices. Likewise, operational productivity in terms of resource utilization and employee productivity received high ratings interpreted as Outstanding Productivity, suggesting that institutional resources and employee performance effectively support organizational operations.**

***Index Terms*—Operational Factors, Operational Productivity, Technology Adoption, Resource Management, Human Resource Practices, Private Higher Education Institutions.**

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I. INTRODUCTION

Private colleges in Valencia City, Bukidnon significantly influence access to education for the area's underserved communities. The region's rural setting creates difficulties, but it simultaneously offers access, this is a strategic spot in Mindanao. These schools encounter many everyday difficulties: funding gaps, old facilities, personnel burdened excessively, and outdated technology. These limitations not only hinder operations, they reduce enrollment, lower program quality, and slow down administrative duties just as the country asks for more skilled graduates. All relies on how well these schools manage their resources, invest in people, improve their processes, and introduce new technology. Focusing on these areas boosts student retention, reduces costs, and increases the speed of their service delivery.

Despite how important these issues are, there is limited research currently accessible regarding what really functions. This study explores how these factors drive productivity in private higher education institutions in Valencia City. It offers practical recommendations which may assist these institutions maintain stability while supporting broader reforms in the context of Philippine higher education.

This study aimed to determine the significant link between operational factors and operational productivity of private higher education institutions in Valencia City, Bukidnon. It focuses on analyzing how technology adoption, resource management, and human resource practices relate to resource utilization and employee productivity. Using a descriptive correlational approach grounded in the Resource-Based View Theory, the research explores the statistical relationships among these variables.

II. LITERATURE REVIEW

In order to give private higher education institutions practical knowledge into their operational changes, the solution is to describe the relationship between operational factors and productivity outcomes rather than proving causation. Operational aspects and productivity metrics are frequently connected. According to Al-Mamun & Fazal, 2018, efficiency and customer satisfaction are positively connected with the implementation of technology. However, because inefficiencies lower overall production, resource waste has a negative correlation with resource utilization (Katua, 2016). Higher productivity levels are consistently linked to human resource management strategies such employee engagement, motivation, and training (Borazon & Supangco, 2020). Operational procedures and resource management have been proven to have a significant effect on private higher education institutions performance in the Philippine environment, highlighting the significance of investigating these linkages in Valencia City.

Moreover, Blended Learning (BL) has increasingly been utilized in higher education as it has the advantages of both traditional and online teaching approaches (Poon 2016). According to Ghazal et al. (2018) findings from prior studies indicated that blended learning approach enhances students'

learning engagement and experience as it creates a significant influence on students' awareness of the teaching mode and learning background.

In another study, the Asian Productivity Organization (2017) emphasized that raising productivity in higher education required strategic management of financial and human resources. The results indicated that institutions implementing resource monitoring systems and performance evaluation mechanisms improved institutional effectiveness and educational outcomes. The study recommended continuous investment in resource planning and management practices.

Allui and Sahni (2016) stated that strategic human resource management practices significantly improved employee performance and institutional effectiveness in higher education institutions. The findings revealed that recruitment, training, compensation, and employee development positively influenced organizational productivity and employee satisfaction. The study emphasized that effective HR practices enhanced institutional competitiveness.

According to Agasisti (2016), the productivity and efficiency of public higher education institutions were greatly influenced by effective resource utilization. The findings indicated that institutions maximizing financial and operational resources achieved higher institutional productivity and sustainability.

Additionally, Menezes (2018) explained that work environment significantly influenced employee productivity in universities. The study found that supportive workplace conditions, effective communication, and positive organizational culture improved employee performance and job satisfaction.

III. MATERIALS AND METHODS

Research Design

This study employed a descriptive correlational research design to investigate the relationships between operational factors; technology adoption, resource management, human resource practices and operational productivity; resource utilization and employee performance in Private Higher Education Institutions in Valencia City, Bukidnon. A descriptive-correlational design is being used in the present study to allow the researchers to describe the present state of the factors and the outcomes of productivity within private higher education institutions. This design allowed the researchers to study the statistical associations of the variables without any manipulation. The descriptive part of the design aimed to develop an accurate depiction of the way private higher education institutions in Valencia City, Bukidnon, presently use of technology, manage their resources, and execute their human resource management practices and how these practices relate to resource management and employee productivity. The correlational part of the design aimed to establish if the factors of institutions operations significantly relate to institutions outcomes.

This quantitative approach described variable levels using means and standard deviations while examining statistical associations via Pearson's correlation coefficient, without implying causality.

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Participants / Respondents

The subject respondents of the study include a total of one hundred (100) consisting of administrative personnel, faculty, and staff from private higher education institutions in Valencia City, Bukidnon. Firstly, these individuals were selected because they are directly involved in operational decision-making, including adopting new technologies, managing resources, and overseeing human resources. Consequently, as primary decision-makers, they are considered the most suitable sources of information regarding operational factors and productivity outcomes in their businesses.

Data Gathering Procedure

The data gathering process followed a systematic and ethical approach to meet institutional guidelines. First, the researchers prepared and sent a formal request letter to the President of IBA College of Mindanao, Inc. The letter explained the objectives, significance, and method of the research to gain institutional approval. Once the researchers have the President's endorsement, the researchers coordinated with other private higher education institutions in Valencia City, Bukidnon, to ask for permission to conduct the study.

After receiving approval from private higher education institutions, the researchers reached out to the institutions Research Director's Office officials to gain access to the respondents. They clearly outlined the purpose and scope of the study to ensure transparency and encourage cooperation. This coordination helped create a schedule for distributing and collecting the research instruments.

Next, the survey questionnaires were given to the respondents selected through stratified random sampling. Before handing out the instrument, the researchers explained the study's objectives, procedures, and expected duration. They obtained informed consent from each participant, highlighting that participation is voluntary and that respondents can withdraw at any time without penalty.

Respondents have enough time to complete the questionnaire, ensuring they can provide thoughtful and accurate responses. The researchers were available during this process to clarify any questions while avoiding any influence on the participants' answers. After completion, the researchers collected and reviewed the questionnaires to ensure all responses are complete and consistent.

Statistical Analysis

To ensure a systematic analysis and a clear interpretation of the data, appropriate statistical tools were used for each problem statement. The choice of statistical methods depended on the nature of the variables and the study's goals. To answer in Problem 1, which seeks to determine the level of operational factors among private higher education institutions in Valencia City, Bukidnon, the mean and standard deviation were used. The mean provided the average responses of the respondents, while the standard deviation measured how much their responses vary. These statistics clearly described the overall level of community preparedness. For Problem 2, which aimed to determine the level of operational productivity, the mean and standard deviation were used. These tools helped the researcher assess the average perception of respondents about public safety

initiatives and determine how consistent their responses are. And for Problem 3, which investigates whether a significant relationship exists between operational factors and operational productivity, the Pearson Product Moment Correlation was also used. All hypotheses were tested at a 0.05 level of significance to determine if there is statistical significance and to guide decision-making regarding the null hypotheses.

IV. RESULTS AND DISCUSSION

Table 1 shows that the overall mean for the respondents' distribution on the level of operational factors as regards to technology adoption is 3.40, with a standard deviation of 0.76, described as Strongly Agree and interpreted as Excellent Implementation. The result indicates that respondents generally perceive the institution as effectively implementing technology in its operations. The relatively moderate standard deviation suggests that respondents' perceptions are fairly consistent. This further implies that technology adoption has become integrated into institutional processes and contributes positively to operational efficiency and educational activities.

Among all survey statements, the highest mean score is 3.64 with a standard deviation of 0.72 for the statement, "Digital tools help make tasks easier and faster." This is described as Strongly Agree and interpreted as Excellent Implementation. The result indicates that respondents strongly recognize the benefits of digital tools in improving efficiency and simplifying tasks within the institution. The relatively low standard deviation suggests that respondents have similar perceptions regarding the usefulness of technology in daily activities. The study's conclusions are corroborated by a study by Venkatesh et al. (2016), which highlighted that people are more inclined to embrace and use technology when they believe it will improve job performance and lessen the effort needed to finish tasks. According to their research, a key factor affecting technology adoption and usage is performance expectancy, or the conviction that technology increases productivity and work efficiency.

Meanwhile, the lowest mean score of 3.19 with a standard deviation of 0.81 was observed in the statements, "Training is provided on how to use new systems or tools" and "The systems used are reliable and rarely have problems." These were described as Agree and interpreted as Adequate Implementation. Although the results remain positive, the lower mean values suggest that respondents perceived these areas less favorably compared to other indicators. The slightly higher standard deviation indicates greater variation in respondents' opinions. The findings of the research are further supported by Tarhini et al. (2017), who noted that system quality and training have a significant effect on user acceptance and technology adoption in educational institutions. According to the study, users are more likely to successfully adopt and use technological systems when they receive sufficient training and when those systems exhibit dependability and usability.

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Table 1

The Level of Operational Factors as regards to Technology Adoption.			
Statements	Mean	Standard Deviation	Description
The institution uses up-to-date technology in its daily operations.	3.40	0.74	Agree
Technology is used in both office work and academic activities.	3.48	0.77	Strongly Agree
Digital tools help make tasks easier and faster.	3.64	0.72	Strongly Agree
The institution keeps up with new technology when needed.	3.29	0.73	Agree
Training is provided on how to use new systems or tools.	3.19	0.81	Agree
The systems used are reliable and rarely have problems.	3.19	0.77	Agree
Technology helps improve communication within the institution.	3.44	0.81	Strongly Agree
Systems and data are used to help in planning and decision-making.	3.46	0.72	Strongly Agree
Online platforms make services more convenient.	3.46	0.76	Strongly Agree
The institution regularly improves its technology.	3.42	0.80	Strongly Agree
Overall	3.40	0.76	Strongly Agree

Legend: 1.00-1.75 Strongly Disagree/Deficient Implementation, 1.76-2.50 Disagree/Limited Implementation, 2.51-3.25 Agree/Adequate Implementation, 3.26-4.00Strongly Agree/Excellent Implementation

Table 2 presents the overall mean of 3.44 with a standard deviation of 0.73, which is described as Strongly Agree and interpreted as Excellent Implementation. The result indicates that respondents generally have positive perceptions regarding the operational factors related to resource management in the institution. The findings suggest that the institution effectively manages and utilizes its resources to support operational activities. Furthermore, the standard deviation shows that respondents' responses are relatively consistent, indicating similar views regarding the institution's resource management practices.

Among all the survey statements, "Equipment and materials are used properly" obtained the highest mean score of 3.54 with a standard deviation of 0.69, which is described as Strongly Agree and interpreted as Excellent Implementation. This indicates that respondents strongly believe that the institution properly utilizes its equipment and materials in carrying out its operations. The relatively low standard deviation suggests that respondents have similar perceptions regarding the

proper use of institutional resources. The study by Aithal and Aithal (2016), which emphasized how efficient use of institutional resources greatly enhances operational efficiency and organizational effectiveness, supports the findings. According to the study, organizations are more likely to increase productivity and improve service quality if they effectively manage and make the most of their resources, equipment, and facilities. The researchers went on to say that effective resource management enables organizations to reduce waste and maximize available resources in order to successfully accomplish their goals.

The statement, "Resources are shared fairly among departments," obtained the lowest mean score of 3.33 with a standard deviation of 0.79, which is described as Agree and interpreted as Excellent Implementation. Although the result remains positive, it received a comparatively lower rating than the other indicators. The higher standard deviation suggests slight differences in the respondents' perceptions regarding the fairness of resource distribution among departments. Mhlanga and Moloi's (2020) study, which brought out the importance of fairness and strategic institutional resource allocation in enhancing organizational effectiveness and operational performance, corroborates the study's conclusions. According to the study, fair and transparent resource distribution fosters efficiency and teamwork while assisting institutions in meeting the diverse needs of various departments.

Table 2

The Level of Operational Factors as regards to Resource Management.			
Statements	Mean	Standard Deviation	Description
Resources are given based on what the institution needs most.	3.39	0.77	Agree
Budget planning supports daily operations.	3.38	0.73	Agree
Facilities are well-maintained and usable.	3.44	0.71	Strongly Agree
Equipment and materials are used properly.	3.54	0.69	Strongly Agree
The use of resources is regularly checked.	3.48	0.72	Strongly Agree
Resources are used in a way that supports smooth operations.	3.52	0.70	Strongly Agree
Purchasing processes are organized and clear.	3.42	0.73	Strongly Agree
Available resources are used as much as possible.	3.46	0.71	Strongly Agree
Resources are shared fairly among departments.	3.33	0.79	Agree
Planning is done to make sure resources last long-term.	3.47	0.72	Strongly Agree

The Level of Operational Factors as regards to Resource Management.			
Statements	Mean	Standard Deviation	Description
Overall	3.44	0.73	Strongly Agree

Legend: 1.00-1.75 Strongly Disagree/Deficient Implementation, 1.76-2.50 Disagree/Limited Implementation, 2.51-3.25 Agree/Adequate Implementation, 3.26-4.00Strongly Agree/Excellent Implementation

Table 3 shows the overall mean of 3.42 with a standard deviation of 0.75, which is described as Strongly Agree and interpreted as Excellent Implementation. This result indicates that respondents generally have positive perceptions regarding the institution's human resource practices. The findings suggest that the institution effectively carries out human resource activities such as recruitment, employee support, performance evaluation, and workplace management. The relatively close responses of the respondents, as indicated by the standard deviation, imply that there is a common perception among them regarding the effectiveness of the institution's human resource practices. Human resource practices are important in ensuring that employees are provided with the support, guidance, and opportunities needed to perform their roles effectively. The positive overall result suggests that the institution recognizes the importance of managing its workforce in achieving organizational goals and maintaining operational efficiency.

Among all survey statements, "The institution hires qualified employees" received the highest mean score of 3.57 with a standard deviation of 0.69, which is described as Strongly Agree and interpreted as Excellent Implementation. This indicates that respondents strongly believe that the institution prioritizes hiring competent individuals who possess the necessary qualifications and skills required for their assigned positions. The relatively low standard deviation suggests that respondents share similar perceptions regarding the institution's recruitment process. The result may indicate that the institution follows specific standards and qualifications during the hiring process to ensure that employees are capable of performing their responsibilities effectively. Recruiting qualified employees is an important aspect of human resource management because it helps improve productivity and supports the institution's ability to meet its objectives. In addition, Singh (2019) stated that hiring qualified employees significantly improves organizational productivity, service quality, and operational performance. Competent employees possess the necessary knowledge and skills to perform work responsibilities effectively, contributing to institutional success. This supports the present findings where respondents strongly agreed that the institution hires qualified employees.

The statement, "Salary and benefits match the work being done," obtained the lowest mean score of 3.18 with a standard deviation of 0.84, which is described as Agree and interpreted as Adequate Implementation. Although respondents still agreed with the statement, the lower mean score compared to the other indicators suggests that compensation and benefits may be an area requiring further attention. The higher standard deviation also indicates some variation in respondents' perceptions, suggesting that experiences and opinions regarding compensation may differ among

employees. Some respondents may perceive that their salaries and benefits appropriately correspond with their responsibilities, while others may feel that their compensation does not fully reflect their workload or job demands. According to Kim (2022), salary and benefits significantly affect employee motivation, job satisfaction, and work performance. Employees who perceive compensation as fair are more likely to remain productive and committed to their responsibilities. This supports the present study where salary and benefits received the lowest mean score among the indicators.

Table 3

The Level of Operational Factors as regards to Resource Management.			
Statements	Mean	Standard Deviation	Description
The institution hires qualified employees.	3.57	0.69	Strongly Agree
Training and development are regularly provided.	3.31	0.78	Agree
Employee performance is reviewed regularly.	3.46	0.74	Strongly Agree
Salary and benefits match the work being done.	3.18	0.84	Agree
Job roles and responsibilities are clearly explained.	3.52	0.69	Strongly Agree
Leaders support employee growth and development.	3.47	0.74	Strongly Agree
The workplace environment is positive and supportive.	3.54	0.71	Strongly Agree
Communication within the institution is clear.	3.40	0.76	Agree
Employee concerns are handled properly.	3.36	0.80	Agree
Policies are applied fairly and consistently.	3.43	0.75	Strongly Agree
Overall	3.42	0.75	Strongly Agree

Legend: 1.00-1.75 Strongly Disagree/Deficient Implementation, 1.76-2.50 Disagree/Limited Implementation, 2.51-3.25 Agree/Adequate Implementation, 3.26-4.00Strongly Agree/Excellent Implementation

Table 4 presents the summary of the respondents' assessment of the operational factors of the institution in terms of Technology Adoption, Resource Management, and Human Resource Practices. The overall mean of 3.42 with a standard deviation of 0.75 is interpreted as Strongly Agree and described as having Excellent Implementation. This result indicates that the respondents generally perceived that the institution effectively implements operational practices that support its daily functions and organizational objectives. The relatively low standard deviation suggests

that the responses were consistent among the respondents. Among the operational factors, Resource Management obtained the highest mean score of 3.44 with a standard deviation of 0.73, interpreted as Strongly Agree and described as Excellent Implementation.

This finding suggests that the institution effectively manages its resources through proper allocation, utilization, monitoring, and planning. The result implies that respondents recognized the institution's efforts in ensuring that resources are available and utilized efficiently to support operational activities. Effective resource management contributes to organizational sustainability and enhances the institution's ability to achieve its goals. Human Resource Practices ranked second with a mean score of 3.42 and a standard deviation of 0.75, interpreted as Strongly Agree and described as Excellent Implementation. This indicates that the institution demonstrates effective practices in hiring qualified personnel, providing training opportunities, evaluating employee performance, and maintaining a supportive work environment.

The finding shows that employees perceive human resource policies and practices as beneficial to their professional growth and organizational performance. Strong human resource practices are essential in fostering employee motivation, commitment, and productivity. Meanwhile, Technology Adoption obtained the lowest mean score of 3.40 with a standard deviation of 0.76, although it still falls within the Excellent Implementation category.

Table 4

Operational Factors Summary Table			
Operational Factors	Mean	Standard Deviation	Description
Resource Management	3.44	0.73	Strongly Agree
Human Resource Practices	3.42	0.75	Strongly Agree
Technology Adoption	3.40	0.76	Agree
Overall	3.42	0.75	Strongly Agree

Legend: 1.00-1.75 Strongly Disagree/Deficient Implementation, 1.76-2.50 Disagree/Limited Implementation, 2.51-3.25 Agree/Adequate Implementation, 3.26-4.00Strongly Agree/Excellent Implementation

Table 5 presents the overall mean of 3.48 with a standard deviation of 0.72, which is described as Strongly Agree and interpreted as Outstanding Productivity. The result indicates that respondents generally have positive perceptions regarding operational productivity in terms of resource utilization within the institution. The findings suggest that resources are effectively managed and utilized to support daily operations and institutional activities. The standard deviation also shows that the responses of the participants are relatively close to one another, indicating consistency in their perceptions regarding the institution's use of resources. Effective resource utilization is

important because it allows institutions to maximize available resources while minimizing unnecessary waste. The overall result suggests that the institution demonstrates efficient practices in handling and managing resources to improve productivity and support organizational performance.

Among all survey statements, "Proper use of resources helps improve overall performance" obtained the highest mean score of 3.59 with a standard deviation of 0.67, which is described as Strongly Agree and interpreted as Outstanding Productivity. This result indicates that respondents strongly recognize the importance of resource utilization in improving institutional performance. The relatively low standard deviation indicates consistency in the respondents' answers, suggesting that most respondents share the same view regarding the impact of resource utilization on productivity. The result highlights that efficient use of available resources contributes significantly to achieving better work outcomes and organizational effectiveness. Daft (2019) explained that proper use of organizational resources improves overall institutional performance by increasing efficiency and supporting the achievement of operational goals. Effective resource utilization allows organizations to improve productivity and service quality. This supports the findings where respondents strongly agreed that proper use of resources improves overall performance.

The statement, "Time is used wisely during work hours," obtained the lowest mean score of 3.38 with a standard deviation of 0.76, which is described as Agree and interpreted as Outstanding Productivity. Although the result still reflects a positive perception, it received a relatively lower rating compared to the other indicators. The standard deviation indicates some variation in responses, which may suggest that respondents have different experiences regarding time management practices within the institution. While many respondents believe that work hours are utilized effectively, some may perceive areas where time management could still be improved. According to Claessens et al. (2019), effective time management is essential in improving productivity and work efficiency. Poor time allocation may affect task completion and operational effectiveness within organizations. This supports the present findings where time utilization during work hours obtained the lowest mean score.

Table 5

The Level of Operational Productivity as regards to Resource Utilization.			
Statements	Mean	Standard Deviation	Description
Resources are used properly in daily work.	3.56	0.68	Strongly Agree
Facilities are used effectively for different activities.	3.50	0.70	Strongly Agree
Budget is used in a way that improves results.	3.44	0.73	Strongly Agree
Work processes help avoid wasting resources.	3.41	0.74	Strongly Agree

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The Level of Operational Productivity as regards to Resource Utilization.			
Statements	Mean	Standard Deviation	Description
Equipment is used properly to complete tasks.	3.52	0.69	Strongly Agree
Different departments work together to use resources better.	3.46	0.73	Strongly Agree
Time is used wisely during work hours.	3.38	0.76	Agree
Resources are given based on priority needs.	3.47	0.72	Strongly Agree
The use of resources is regularly checked for effectiveness.	3.43	0.74	Strongly Agree
Proper use of resources helps improve overall performance.	3.59	0.67	Strongly Agree
Overall	3.48	0.72	Strongly Agree

Legend: 1.00-1.75 Strongly Disagree/ Poor Productivity, 1.76-2.50 Disagree/ Inadequate Productivity, 2.51-3.25 Agree/Satisfactory Productivity 3.26-4.00Strongly Agree/Outstanding Productivity

Table 6 presents an overall mean of 3.55 with a standard deviation of 0.69, which is described as Strongly Agree and interpreted as Outstanding Productivity. The findings indicate that respondents generally have highly positive perceptions regarding employee productivity within the institution. The result suggests that employees are able to perform their responsibilities effectively and contribute positively to organizational performance. The relatively low standard deviation also indicates that respondents have similar perceptions regarding employee productivity, showing consistency in their responses. Employee productivity plays an important role in organizational success because it directly influences the quality of work output, efficiency in completing tasks, and the achievement of institutional objectives. The overall result suggests that the institution maintains productive employees who are capable of meeting expectations and supporting the institution's operational performance.

Among all survey statements, “Teamwork helps in completing tasks” obtained the highest mean score of 3.62 with a standard deviation of 0.65, which is described as Strongly Agree and interpreted as Outstanding Productivity. This result indicates that respondents strongly recognize the importance of teamwork in improving employee productivity and completing work responsibilities effectively. The relatively low standard deviation indicates consistency in responses, suggesting that respondents have similar perceptions regarding the positive impact of teamwork within the institution. Effective teamwork allows employees to share ideas, divide responsibilities, and work together toward common goals, which can improve work performance and productivity. Robbins and Judge (2019) emphasized that teamwork improves employee productivity, communication, and task completion. Employees who collaborate effectively are

more capable of achieving organizational goals and maintaining operational efficiency. This supports the findings where teamwork obtained the highest mean score.

The statement, "Productivity is maintained at a consistent level," obtained the lowest mean score of 3.46 with a standard deviation of 0.73, which is still described as Strongly Agree and interpreted as Outstanding Productivity. Although the result remains highly positive, it received the lowest score among the indicators presented. The standard deviation suggests slight variations in respondents' perceptions, which may indicate that some respondents experience differences in maintaining productivity levels over time. Factors such as workload, changing responsibilities, and work-related challenges may influence consistency in productivity. According to Muda et al. (2018), maintaining consistent productivity may become challenging due to workload demands, changing responsibilities, and workplace conditions. Continuous support and professional development are important in sustaining employee performance over time. This supports the findings where maintaining productivity at a consistent level obtained the lowest mean score.

Table 6

The Level of Operational Productivity as regards to Employee Productivity.			
Statements	Mean	Standard Deviation	Description
Tasks are completed on time.	3.55	0.69	Strongly Agree
Work output meets expected quality.	3.57	0.67	Strongly Agree
Work contributes to the institution's goals.	3.60	0.66	Strongly Agree
Tasks are done efficiently.	3.53	0.69	Strongly Agree
Initiative is shown in completing work.	3.50	0.71	Strongly Agree
Productivity is maintained at a consistent level.	3.46	0.73	Strongly Agree
Employees adjust well to changes in work.	3.48	0.72	Strongly Agree
Teamwork helps in completing tasks.	3.62	0.65	Strongly Agree
Work performance contributes to institutional success.	3.58	0.67	Strongly Agree
Efforts are made to improve performance over time.	3.59	0.66	Strongly Agree
Overall	3.55	0.69	Strongly Agree

Legend: 1.00-1.75 Strongly Disagree/ Poor Productivity, 1.76-2.50 Disagree/ Inadequate Productivity, 2.51-3.25 Agree/Satisfactory Productivity 3.26-4.00Strongly Agree/Outstanding Productivity

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Table 7 presents the summary of respondents' assessment of operational productivity among private higher education institutions in Valencia City, Bukidnon. The overall mean score of 3.52 and standard deviation of 0.71 indicate that respondents strongly agree that their institutions exhibit a high level of operational productivity, which is interpreted as Outstanding Productivity. This suggests that the institutions are effective in maximizing available resources and maintaining employee efficiency to achieve organizational objectives.

Among the indicators, Employee Productivity obtained the highest mean score (M = 3.55, SD = 0.69), indicating that employees consistently perform their responsibilities efficiently, demonstrate commitment to their work, and contribute positively to institutional performance. The low variability in responses further suggests a strong consensus among respondents regarding the productive performance of employees.

Meanwhile, Resource Utilization recorded a mean score of 3.48 (SD = 0.72), which is likewise interpreted as Outstanding Productivity. This finding implies that institutional resources, including facilities, equipment, finances, and other operational assets, are effectively managed and utilized to support organizational functions. Respondents perceive that resources are allocated appropriately and are used in a manner that promotes efficiency and productivity.

The findings reveal that private higher education institutions have successfully maintained productive operations through effective resource management and a highly performing workforce. The consistently high ratings across both indicators suggest that these institutions have established operational practices that support efficiency, effectiveness, and the achievement of institutional goals. Such outcomes may contribute to improved service delivery, enhanced organizational performance, and sustained institutional competitiveness.

Table 7

Operational Productivity Summary Table			
Operational Productivity	Mean	Standard Deviation	Description
Resource Utilization	3.48	0.72	Strongly Agree
Employee Productivity	3.55	0.69	Strongly Agree
Overall	3.52	0.71	Strongly Agree

Legend: 1.00-1.75 Strongly Disagree/ Poor Productivity, 1.76-2.50 Disagree/ Inadequate Productivity, 2.51-3.25 Agree/Satisfactory Productivity 3.26-4.00Strongly Agree/Outstanding Productivity

Table 8 presents the correlation between operational factors and operational productivity in terms of resource utilization and employee productivity. The results show that all computed p-values are greater than the 0.05 level of significance, indicating that there is no significant relationship

between the variables. Technology adoption showed weak positive relationships with both resource utilization (r = .186, p = .612) and employee productivity (r = .241, p = .502). Resource management also showed positive relationships with resource utilization (r = .408, p = .241) and employee productivity (r = .376, p = .285), but these were not significant. Human resource practices obtained r = .298 (p = .404) for resource utilization and r = .628 (p = .052) for employee productivity, which also remained not significant. The findings imply that operational factors such as technology adoption, resource management, and human resource practices do not have a significant relationship with operational productivity in terms of resource utilization and employee productivity. Although positive relationships were observed, they were not statistically significant. Therefore, the results suggest that operational productivity may be influenced by other factors not included in the study. The study of Al-Omari and Okasheh (2017), which highlighted that employee productivity and organizational performance are influenced by multiple interacting factors rather than a single operational component, supports the current study's findings. Workplace conditions, organizational environment, management support, and employee-related factors may all have an impact on productivity outcomes, according to the researchers.

Table 8

Variables	Resource Utilization		Int	Employee Productivity		Int
	r-value	p-value		r-value	p-value	
Technology Adoption	.186	.612	NS	.241	.502	NS
Resource Management	.408	.241	NS	.376	.285	NS
Human Resource Practices	.298	.404	NS	.628	.052	NS

Correlation is significant at the 0.05 level (two tailed).
NS = Not Significant

Table 9 presents the relationship between operational factors and operational productivity. The computed r-value of .214 indicates a weak positive relationship between the variables. However, the p-value of .553 is greater than the 0.05 level of significance, indicating that the relationship is not statistically significant. Therefore, the null hypothesis (Ho) was accepted. This means that operational factors do not show a significant relationship with operational productivity among the respondents.

The findings imply that operational factors may not significantly influence operational productivity in the institution. Although a positive relationship was observed, it was not strong enough to establish statistical significance. This suggests that other factors not included in the study may also affect operational productivity.

The findings of the study are supported by the study of Pawirosumarto et al. (2017), which stated that organizational productivity and employee performance are influenced by various interrelated factors, including leadership, work environment, motivation, and organizational support systems. The researchers emphasized that although operational practices may contribute to productivity, the

presence of multiple influencing variables may reduce the direct impact of a single factor on organizational outcomes. The study further explained that productivity is a multidimensional concept that cannot be solely explained by operational indicators. This supports the findings of the present study wherein operational factors demonstrated a weak positive relationship with operational productivity but did not show a statistically significant association.

Table 9

Variables		r-value	p-value	Decision on Ho	Interpretation
Operational Factors	Operational Productivity	.214	.553	Accept Ho	Not Significant

Correlation is significant at the 0.05 level (two tailed).
NS = Not Significant

V. CONCLUSION

Based on the findings of the study, it is concluded that private higher education institutions demonstrate effective implementation of operational factors and maintain satisfactory levels of operational productivity. The institution appears to effectively utilize technology, manage resources, and implement human resource practices that support its daily functions and activities. Despite the positive perceptions regarding these operational factors, the statistical analysis showed that they do not significantly influence operational productivity when examined independently.

The study concludes that private higher education institutions in Valencia City, Bukidnon demonstrate a high level of operational productivity in terms of resource utilization and employee productivity. Respondents perceived that institutional resources are effectively allocated, monitored, and utilized to support daily operations, while employees consistently perform their duties efficiently and contribute to the achievement of organizational goals. The overall ratings of Outstanding Productivity indicate that the institutions have established effective practices that promote efficient resource use and high employee performance.

The study concludes that there is no significant relationship between operational factors and operational productivity among private higher education institutions in Valencia City, Bukidnon. Although technology adoption, resource management, and human resource practices were positively perceived and showed weak positive correlations with resource utilization and employee productivity, the relationships were not statistically significant. Therefore, the null hypothesis was accepted. This suggests that operational productivity may be influenced by other organizational and environmental factors not included in the study, such as leadership, work environment, employee motivation, and institutional support systems.

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A Comparative Study of Customer Satisfaction Between Physical Stores and Online Shops Among the Faculty and Staff of IBA College Of Mindanao, Inc.

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***Abstract*—This study aimed to determine the shopping preferences and customer satisfaction among the Faculty and Staff of Irene B. Antonio College of Mindanao, Inc. Specifically, it investigates the level of shopping preferences when they shop in terms of physical store and online store, determine the level of customer satisfaction when they shop in online stores in terms of shopping experience, willingness to repurchase, convenience, and examine the significant differences between the customer when they are grouped according to shopping preferences. Using a comparative research design, 68 full-time faculty and staff were purposively selected, and data were collected through a survey questionnaire and researcher-made instrument. Statistical analyses, including mean, standard deviation, and T-test, were applied to measure the significant relationship between shopping preferences and customer satisfaction. Findings revealed that the majority of the respondents preferred shopping in physical stores rather than online shops. In terms of customer satisfaction, the respondents showed a high level of satisfaction across the three dimensions: shopping experience, willingness to repurchase, and convenience. The findings suggest that faculty and staff still value the direct interaction, product inspection, and immediate availability of products offered by physical stores despite the increasing popularity of online shopping platforms. The study recommends to constantly improve both physical and online shopping**

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experiences by emphasizing customer convenience, product quality, and efficient service delivery.

Index Terms—Customer satisfaction, Shopping preferences, Online shops, Physical stores, Faculty and staff of IBA College of Mindanao Inc.

I. INTRODUCTION

The increasing frequency of online shopping has significantly altered consumer behavior, especially among the faculty and staff of Irene B. Antonio College of Mindanao, Inc., in Valencia City Bukidnon. Prompted by the COVID-19 pandemic, the faculty and staff have increasingly turned to online store for their purchases due to the convenience of browsing a wide selection of products, access to discounts and vouchers, and the option to have parcels delivered directly to the schools or house. However, physical stores continue to play a significant role for urgent purchases, especially when faculties need items immediately or when specific products are unavailable online. This blend of shopping behaviors reflects a unique dynamic between physical stores and online stores in meeting the needs of the Faculty and Staff of the IBA College of Mindanao Inc. Online shops offer a broader range of products, convenient price comparisons, and the flexibility to shop anytime and anywhere. While online shopping has become essential to modern commerce, it also poses challenges like fraud risk, delayed deliveries, and the inability to physically inspect products. Physical store is a retail environment that requires tangible space for displaying and marketing products, while online platforms are preferred for their accessibility and convenience, physical stores are favored for the ability to physically inspect products and receive immediate assistance from sales staff. These factors make traditional retail experiences appealing to certain segments of young consumers, underscoring the coexistence of both shopping modes in their purchasing behavior.

The results of the study aids in determining which retail setting best suits the demands of teachers, directing enhancements in technology integration, service delivery, and transaction fairness. Ultimately, this study contributes to academic discussions while additionally providing retailers seeking to improve customer satisfaction in traditional and online marketplace with useful information.

II. LITERATURE REVIEW

Prior to the digital revolution, shopping at physical stores was typically improved by well-designed interiors that displayed merchandise in settings reminiscent of museums and offered quiet spaces like on-site cafes. The retailer had top-down control over the customer experience. Consumers today are more digitally savvy, have higher expectations, and seek out a greater range of stimuli, including information, suggestions, usability, customization, and engagement. As a result, retailers are paying close attention to creating a satisfying shopping experience across all of their channels. Today's physical store needs to offer a dynamic experience where customers can actively design

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their own shopping path, rather than one that is static. This type of experience includes inclusion and involvement (Fontana et al., 2021).

Moreover, according to Neslin (2022) long-term consumer value is increased when deep products are purchased in-store. Customers who buy deep products in-store are more inclined to buy similar and related deep product categories online. Experiential learning is a significant underlying mechanism. For instance, it is different from experience/search in that a deep product only has to be examined; it is not necessary to consume it in order to evaluate it. It brings digital characteristics into the real world, such appearance.

In contrast, customers who are more seasoned online shoppers typically make larger purchases (Braimllari et al. 2021). According to Petrock (2021), Gen Z is the first generation to have constant access to social media, connected devices, and the internet. Also, according to Kemp (2021), Filipinos spend an average of 10 hours and 56 minutes on the Internet, where they can find information about various electronic products and their features, as well as enticing ads that encourage them to buy products from Shopee, where the majority of Generation Z customers, who are between the ages of 18 and 24, make online purchases.

Customer satisfaction based on convenience, shopping experience, and willingness to repurchase are some of the factors that affect customer satisfaction, which is a crucial component of retail success. Furthermore, convenience plays a significant part in determining customer satisfaction, with both physical stores and online platforms providing unique benefits. Physical stores give customers instant access to merchandise, enabling them to evaluate it in person and make purchases without having to wait for delivery. However, there may be limited operating hours, crowded areas, and travel time associated with shopping in physical stores. People's perceptions of privacy and personal space vary depending on the circumstances they encounter, as noted by Esmark and Noble (2016).

In addition, according to Angelito Jr P. (2024) Filipinos have become increasingly discerning and demanding of the internet purchase experience itself. Customers can also inspect the merchandise more closely. People without access to the Internet can shop in physical stores after making a payment; the product will be available immediately. It's easier to return products, tactile store purchasing gives a tactile and sensory experience, which is especially crucial for things such as apparel, furnishings, and cosmetics, where the ability to touch, feel, and try on items is required. The layout, ambiance, and physical environment of the business can all have an impact on the overall shopping experience.

Subsequently, according to Stephani et al. (2018), is the probability that consumers will use goods or services they have already purchased again. They maintained that keeping customers' intention to repurchase is crucial. Repurchase intention, according to Lee, HJ (2020), is the probability of making a repeat buy of specific goods or services from the same business, mostly as a result of prior purchases. Repurchase intention in the retail cosmetics industry not only saves money for companies but also shows how strong the brand is.

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Convenience and accessibility are the main draws of online shopping. According to earlier research, the main elements influencing consumers' happiness with online purchasing are simplicity of use, time savings, and convenience. Online customers place a high value on delivery speed, payment security, and website usability, claim Kim & Park (2020).

III. MATERIALS & METHODS

Research Design

This study employed a comparative research design to compare customer satisfaction between physical stores and online shops. Comparative design is appropriate because it facilitates the systematic identification of similarities and differences in customer interactions across different retail environments. A survey was conducted among 68 full-time faculty and staff of Irene B. Antonio College of Mindanao, Inc. using a questionnaire and researcher-made instrument.

Respondents

The respondents of the study were consisted of sixty-eight (68) full-time faculty and staff of Irene B. Antonio College of Mindanao, Inc. These individuals were selected to provide relevant information regarding shopping preferences and customer satisfaction with the locality. The respondents were considered appropriate participants because they were the actual consumers and employees of the institution and were therefore capable of sharing their perceptions and experiences related to purchasing behavior. The study employed a purposive sampling to select the total enumeration of full-time Faculty and Staff who engage in shopping either at physical stores or through online platforms. The selected participants would be deemed sufficient to provide the necessary and relevant data. Their responses generated valuable insights that contributed to effectively addressing the research questions.

Data Gathering Procedure

The research data was collected in a systematic and ethical way which is in adherence to institutional and community protocols using a survey questionnaire. Following the approval of local authorities, the researcher formally communicated with barangay officials to facilitate access to the respondents. The purpose and scope of the study were clearly explained to ensure transparency and cooperation. This coordination helped establish an organized schedule for the distribution and retrieval of the research instruments. Consequently, the survey questionnaires were administered to the selected one hundred respondents through simple random sampling. Once the surveys were completed, the responses were tallied and analyzed for statistical significance using appropriate methods.

Statistical Analysis

To be certain, the researchers did a systematic analysis and accurate interpretation of the data which the researchers achieved by used of appropriate statistical tools for each issue at hand. Which the researchers chose based on the type of variables the researchers had and the study’s goals. Likert

scale, 30 items, Cronbach's Alpha 0.95, interpreted as excellent and indicated as reliable. To answer Problem 1, they determined the level of shopping preferences, mean and standard deviation was used. For Problem 2, they examined the level of customer satisfaction, they also reported mean and standard deviation. And for Problem 3 they observed the significant relationship between shopping preferences and customer satisfaction.

IV. RESULTS AND DISCUSSION

Table 1 shows that respondents were highly satisfied with their preferred shopping method, as shown by an overall mean score of 3.43 with a standard deviation of 0.60, interpreted as "Strongly Agree" and "Highly Satisfied." This indicates that respondents mostly rated their shopping experiences positively in terms of convenience, product quality, pricing, reliability, customer service, and purchasing experience. The comparatively low standard deviation implies that the participants' responses were consistent, indicating a shared perception of satisfaction among the respondents.

Among all the indicators, the statement "The available payment options are convenient and easy to use" received the highest mean score of 3.57 with a standard deviation of 0.53, interpreted as "Strongly Agree" and "Highly Satisfied." This shows that respondents strongly valued the accessibility and convenience of the payment methods offered by their preferred shopping platform. The low standard deviation indicates that respondents had comparable positive perceptions of the effectiveness and usability of available payment systems. Hagtvedt and Chandukala (2023) find that simpler payment systems and convenient shopping methods improve customer satisfaction and loyalty. According to their findings, consumers are more satisfied when retailers offer seamless and user-friendly transaction processes.

The indicator "The time required to complete my purchase is satisfactory" received the lowest mean score of 3.26 with a standard deviation of 0.68, however it remains interpreted as "Strongly Agree" and "Highly Satisfied." This suggests that, while respondents remained satisfied with the purchasing process, some participants may have encountered minor delays or inconveniences in completing their purchases. The relatively higher standard deviation also shows more variation in respondents' experiences with transaction time than the other indicators. Duarte, e Silva, and Ferreira (2018) established that convenience and efficiency in purchasing procedures have a substantial influence on customer satisfaction, particularly in online shopping environments. According to their study, consumers place a high value on time-saving features and efficient service delivery.

Table 1

The Level of Customer Satisfaction as regards to Shopping Experience.			
Statements	*Mean*	*Standard Deviation*	*Description*
I am satisfied with my overall shopping experience using my preferred shopping method.	3.52	0.59	Strongly Agree
I am satisfied with the quality of the products I purchase.	3.40	0.60	Strongly Agree

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The Level of Customer Satisfaction as regards to Shopping Experience.			
Statements	*Mean*	*Standard Deviation*	*Description*
The prices of the products I buy are reasonable.	3.43	0.58	Strongly Agree
There is a wide variety of products available when I shop.	3.43	0.63	Strongly Agree
Purchasing products using my preferred shopping method is convenient.	3.55	0.53	Strongly Agree
The time required to complete my purchase is satisfactory.	3.26	0.68	Strongly Agree
The store or seller where I usually purchase products is reliable.	3.35	0.62	Strongly Agree
I receive good customer service when making purchases.	3.32	0.61	Strongly Agree
The available payment options are convenient and easy to use.	3.57	0.53	Strongly Agree
I am satisfied with my purchasing experience.	3.47	0.59	Strongly Agree
Overall	3.43	0.60	Strongly Agree

Legend 1.00–1.75 Strongly Disagree/Not Satisfied at All, 1.76–2.50 Disagree/Less Satisfaction, 2.51–3.25 Agree/Satisfied, 3.26–4.00 Strongly Agree/Highly Satisfied

Table 2 shows that respondents demonstrated a high level of willingness to repurchase products using their preferred shopping method, as evidenced by an overall mean score of 3.45 with a standard deviation of 0.58, which is interpreted as "Strongly Agree" and "Highly Satisfied." This suggests that respondents generally expressed positive intentions to continue using their preferred platform. The consistently high mean scores across all indicators suggest that respondents were pleased with their shopping experiences, trusted the shopping method, and intended to continue purchasing products in the future.

The indicator "Overall, I am willing to repurchase products using this shopping method" also received the highest mean score of 3.51 with a standard deviation of 0.56, which is equivalent to "Strongly Agree" and "Highly Satisfied." This indicates that respondents generally maintained a strong intention to continue purchasing products using their preferred shopping method in the future. The low standard deviation demonstrates respondents' consistent optimistic views toward repurchasing behavior. Chan et al. (2017) supports the findings, claiming that purchase intention and prospective preference potential are significant predictors of future consumer behavior. According to their findings', satisfied customers are more likely to buy from the same seller or platform again. Furthermore, Soeharso et al. (2024) showed that customer satisfaction has a significant influence on repurchase intention and customer loyalty in the retail industry.

The indicator "I am confident that I will continue using this shopping method regularly" received the lowest mean score of 3.34 with a standard deviation of 0.56, but it was still interpreted as "Strongly Agree" and "Highly Satisfied." This suggests that, while respondents typically showed confidence in using their preferred shopping method on a regular basis, some may still have reservations about continuous long-term use. The standard deviation indicates minor variations in respondents' perceptions of regular use of the shopping method. Matute et al. (2016) support the findings, stating that trust and digital referrals have a significant influence on consumers repurchase

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intentions and continued use of online shopping platforms. Furthermore, Alrawad et al. (2023) stated that customer trust, perceived security, and previous shopping experiences have an important influence on consumers' willingness to continue engaging in online shopping activities.

Table 2

The Level of Customer Satisfaction as regards to Willingness to Repurchase.			
Statements	*Mean*	*Standard Deviation*	*Description*
I am willing to purchase products again using my preferred shopping method.	3.51	0.53	Strongly Agree
I intend to continue buying products using my preferred shopping method in the future.	3.50	0.53	Strongly Agree
I would consider purchasing again from the same store or seller.	3.42	0.63	Strongly Agree
I am likely to choose this shopping method again for future purchases.	3.47	0.61	Strongly Agree
I would recommend this shopping method to others.	3.37	0.69	Strongly Agree
I prefer using this shopping method when buying products.	3.41	0.55	Strongly Agree
I am confident that I will continue using this shopping method regularly.	3.34	0.56	Strongly Agree
My experience encourages me to make future purchases using this shopping method.	3.47	0.59	Strongly Agree
I trust this shopping method when making purchasing decisions.	3.47	0.59	Strongly Agree
I am willing to repurchase products using this shopping method.	3.51	0.56	Strongly Agree
Overall	3.45	0.58	Strongly Agree

Legend 1.00–1.75 Strongly Disagree/Not Satisfied at All, 1.76–2.50 Disagree/Less Satisfaction, 2.51–3.25 Agree/Satisfied, 3.26–4.00 Strongly Agree/Highly Satisfied

Table 3 shows that respondents were highly satisfied with the convenience of their preferred shopping method, as shown by an overall mean score of 3.47 with a standard deviation of 0.63, interpreted as "Strongly Agree" and "Highly Satisfied." This indicates that respondents generally perceived their shopping method to be efficient, accessible, and user-friendly. The consistently high mean scores across all indicators indicate that respondents were satisfied with the simple nature of the purchasing process, ease of access, payment convenience, and ability to shop efficiently on their preferred shopping platform. The findings implied that convenience has significant effects on customer satisfaction and shopping preferences. Consumers prefer shopping methods that enable them to purchase products quickly, save time, and complete transactions efficiently. The findings additionally indicate that accessible platforms, simpler purchasing methods, and convenient payment systems improve consumers' shopping experiences and motivate individuals to continue

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using their preferred shopping method. As a result, businesses should constantly improve convenience-related services to maintain customer satisfaction and loyalty.

Among all the indicators, the statement "The payment process is simple and convenient" received the highest mean score of 3.63 with a standard deviation of 0.55, interpreted as "Strongly Agree" and "Highly Satisfied." This indicates that respondents were highly satisfied with the convenience and simplicity of the payment process provided by their preferred shopping method. The low standard deviation indicates that respondents held consistent positive attitudes toward the accessibility and efficiency of payment procedures. Hagtvedt and Chandukala (2023) support this finding, emphasizing that convenience-oriented retail strategies, such as simplified payment systems, significantly increase customer satisfaction and loyalty. Furthermore, Secretaria et al. (2021) emphasized that customers are more likely to trust and continue to buy from shopping platforms that offer easy and convenient payment options.

The indicator "My preferred shopping method saves me time when purchasing products" received the lowest mean score of 3.32 with a standard deviation of 0.74, however it was still interpreted as "Strongly Agree" and "Highly Satisfied." This suggests that, while most respondents agreed that their preferred shopping method saves time, some may have encountered delays or inconveniences during the purchasing process. The relatively higher standard deviation indicates greater variation in respondents' perceptions of time efficiency. Melaragno (2019) supports the findings, stating that modern shops improve customer convenience by adopting techniques that reduce consumers' time and effort during purchasing transactions. Similarly, Bulacan et al. (2022) discovered that time efficiency is a crucial factor influencing consumers' online purchasing behavior in the Philippines, indicating that customers prefer platforms that deliver faster and more comfortable shopping experiences.

Table 3

The Level of Customer Satisfaction as regards to Convenience.			
Statements	*Mean*	*Standard Deviation*	*Description*
My preferred shopping method allows me to purchase products easily.	3.47	0.61	Strongly Agree
It is easy for me to find the products I want using my preferred shopping method.	3.41	0.63	Strongly Agree
I can complete my purchases quickly using this shopping method.	3.46	0.61	Strongly Agree
My preferred shopping method saves me time when purchasing products.	3.32	0.74	Strongly Agree
The process of ordering or buying products is simple.	3.51	0.56	Strongly Agree
I can shop at any time using this shopping method.	3.41	0.70	Strongly Agree
The steps involved in making a purchase are easy to understand.	3.58	0.55	Strongly Agree

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The Level of Customer Satisfaction as regards to Convenience.			
Statements	*Mean*	*Standard Deviation*	*Description*
The payment process is simple and convenient.	3.63	0.55	Strongly Agree
I can easily access the store or platform when I want to purchase products.	3.43	0.72	Strongly Agree
My preferred shopping method provides a convenient way to shop.	3.50	0.63	Strongly Agree
Overall	3.47	0.63	Strongly Agree

Legend 1.00–1.75 Strongly Disagree/Not Satisfied at All, 1.76–2.50 Disagree/Less Satisfaction, 2.51–3.25 Agree/Satisfied, 3.26–4.00 Strongly Agree/Highly Satisfied

The faculty and staff at IBA College of Mindanao's customer satisfaction rating is summarized in Table 4. According to the findings, every sub variable had mean scores that fell into the Strongly Agree category and were deemed Highly Satisfied. Convenience had the highest mean score (3.47 with a standard deviation of 0.63) among the dimensions, followed by Willingness to Repurchase (3.45 with a standard deviation of 0.58) and Shopping Experience (3.43 with a standard deviation of 0.60). The respondents' overall mean score of 3.45, with a standard deviation of 0.61, shows that they are generally quite satisfied with their shopping experiences and preferences. The findings indicates that respondents are generally satisfied with the factors influencing their purchasing behavior and have a positive perception of their shopping experiences. The higher convenience rating indicates that respondents value accessibility, ease of purchase, and the effectiveness of their preferred method of shopping more. Similarly, the positive ratings for willingness to repurchase show that respondents have a high degree of confidence and trust in their shopping experiences. The results also suggests that practical and service-related elements that contribute to a satisfying shopping experience have an effect on faculty and staff customer satisfaction.

The study of Rita et al. (2019), which highlighted that convenience, service quality, and the overall shopping experience have a significant effect on customer satisfaction, supports the results of this study. The researchers clarified that when shopping methods are accessible, user-friendly, and capable of fulfilling their expectations, consumers typically exhibit higher levels of satisfaction. The study also showed that consumers' intentions to stick with a shopping strategy and refer others to it are strongly influenced by customer satisfaction. This supports the results of the present research, which showed that respondents had high satisfaction levels in terms of convenience, willingness to repurchase, and shopping experience, suggesting that positive shopping experiences influence customer satisfaction and future purchasing behavior.

Table 4

Customer Satisfaction Summary Table.			
Sub-variables	*Mean*	*Standard Deviation*	*Description*
Shopping Experience	3.43	0.60	Strongly Agree
Willingness to Repurchase	3.45	0.58	Strongly Agree

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Customer Satisfaction Summary Table.			
Sub-variables	*Mean*	*Standard Deviation*	*Description*
Convenience	3.47	0.63	Strongly Agree
Overall	3.45	0.61	Strongly Agree

Legend 1.00–1.75 Strongly Disagree/Not Satisfied at All, 1.76–2.50 Disagree/Less Satisfaction, 2.51–3.25 Agree/Satisfied, 3.26–4.00 Strongly Agree/Highly Satisfied

Tables 5 and 6 presented the difference in customer satisfaction when grouped according to shopping preference. Table 5 specifically presents the differences in the dimensions of customer satisfaction between online shopping and physical store shopping. The results revealed that no significant differences were observed across most dimensions, except for convenience. In this dimension, respondents who preferred online shopping reported significantly higher satisfaction compared to those who preferred physical stores ($t(64) = -2.05$, $p = .044$). On the other hand, Table 6 presents the overall difference in customer satisfaction when grouped according to shopping preference. The computed result ($t(64) = -1.09$, $p = .279$) indicates that there is no statistically significant difference in overall customer satisfaction between the two groups. These findings suggested that although online shoppers perceived greater convenience compared to customers who preferred physical stores, this difference was not substantial enough to influence the overall level of customer satisfaction. Hence, the null hypothesis is not rejected. The study by Rita et al. (2019), which highlighted how convenience greatly influences consumer perceptions and purchasing behavior, supports the current study's conclusions. Customers are more likely to favor shopping strategies that reduce effort, save time, and make transactions simple, according to the researchers. Additionally, the study demonstrated how convenience affects consumer satisfaction and behavioral intentions, especially when consumers perceive variations in usability and accessibility between shopping methods. This aligns with the results of this study, which indicated that respondents' preferred shopping methods have an influence on their perceptions of convenience. Convenience demonstrated a significant difference according to shopping preference.

Table 5

Grouping Variable	Dependent Variable	T	df	p-value
Shopping Preference	Shopping Experience	-1.18	64	.243
	Willingness to Repurchase	0.37	64	.710
	Convenience	-2.05*	64	.044

**. p<0.05, **. p<0.01*

Table 6

Grouping Variable	Dependent Variable	T-statistics	df	p-value	Decision on H_0	Interpretation
Shopping Preference	Customer Satisfaction	-1.09	64	.279	Fail to Reject	Not Significant

**. p<0.05, **. p<0.01*

V. CONCLUSION

The study concluded that the majority of the faculty and staff of IBA College of Mindanao, Inc. prefer shopping in physical stores rather than online shops. Respondents value the opportunity to personally inspect products, interact directly with sellers, and receive purchased items immediately. Although online shopping offers convenience and accessibility, physical stores remain the more preferred shopping platform among the respondents.

The study concluded that the faculty and staff exhibit a high level of customer satisfaction across all dimensions, namely shopping experience, willingness to repurchase, and convenience. All indicators were rated as "Highly Satisfied," demonstrating that respondents have positive perceptions of their preferred shopping method. Among the three dimensions, convenience emerged as the strongest factor contributing to customer satisfaction, indicating that accessibility, ease of use, and time-saving benefits are highly valued by consumers.

The study concluded that there is no significant difference in the overall customer satisfaction of respondents when grouped according to shopping preference. While online shoppers reported significantly higher satisfaction in terms of convenience, the difference was not sufficient to create a significant variation in overall customer satisfaction between those who preferred physical stores and those who preferred online shops. Therefore, both shopping platforms are capable of providing satisfactory shopping experiences to consumers.

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Simultaneous Chromatographic Determination of Proguanil and Atovaquone: A Comprehensive Review Of RP-HPLC, UPLC, And Stability-Indicating Methodologies

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***Abstract*—Proguanil hydrochloride and atovaquone represent a cornerstone fixed-dose combination therapy vital to global multi-drug-resistant *Plasmodium falciparum* malaria management. Due to the extreme divergence in their chemical polarities and asymmetric dose ratios (typically 100 mg to 250 mg), establishing unified quality control protocols presents unique analytical challenges. This comprehensive review synthesizes contemporary Reversed-Phase High-Performance Liquid Chromatography (RP-HPLC), stability-indicating assays, and ultra-performance liquid chromatography (UPLC) methods engineered for their simultaneous estimation. We critically evaluate data across published parameters—comparing C18 versus C8 stationary phases, isocratic versus gradient elutions, mobile phase selections (utilizing volatile formate, acetate, or phosphate aqueous buffers paired with acetonitrile or methanol), and spectrophotometric uv wavelengths. Validation benchmarks matching ICH Q2(R1) specifications—specifically linearity, exact percentage recovery values, sensitivity metrics (LOD/LOQ), system suitability indicators, and robustness under stress—are systematically evaluated. Finally, the article highlights the industry's shift toward Green Analytical Chemistry (GAC), detailing techniques designed to maximize throughput while minimizing toxic solvent waste.**

***Index Terms*—Atovaquone, Proguanil Hydrochloride, RP-HPLC, Method Validation, Forced Degradation Review.**

I. INTRODUCTION

Malaria continues to stand as one of the most devastating tropical diseases globally, inflicting severe morbidity and economic strain on developing countries. Among the available therapeutic

regimens, the fixed-dose combination of Proguanil Hydrochloride and Atovaquone has emerged as a premier, first-line synergistic treatment, widely prescribed for both the prophylaxis and acute treatment of multi-drug-resistant *Plasmodium falciparum* malaria. Proguanil acts as a biguanide prodrug whose active metabolite selectively inhibits the parasite's dihydrofolate reductase enzyme, while atovaquone functions as a highly lipophilic hydroxy-1,4-naphthoquinone that collapses the parasite's mitochondrial membrane potential. Together, they successfully block separate pathways in the organism, which drastically minimizes the emergence of drug resistance and ensures excellent clinical outcomes.

To maintain the absolute safety, purity, and potency of this co-formulated regimen, pharmaceutical manufacturing demands highly reliable and stringent quality control protocols. Reversed-Phase High-Performance Liquid Chromatography (RP-HPLC) has established itself as the analytical cornerstone for these quality control operations. However, establishing a single method for this binary mixture presents a unique challenge due to the immense polarity differences between the two drugs. Proguanil is exceptionally polar and water-soluble, whereas atovaquone is fiercely hydrophobic and practically insoluble in aqueous media. Furthermore, commercial formulations (such as Malarone) exhibit a skewed therapeutic dosage ratio, typically pairing 250 mg of atovaquone with 100 mg of proguanil. This structural asymmetry frequently leads to split peaks, poor selectivity, or excessive peak tailing if the stationary phase chemistry, buffer pH, and mobile phase systems are not meticulously balanced.

Consequently, regulatory bodies like the International Council for Harmonisation (ICH) and the USFDA mandate that any routine or stability-indicating assay must undergo an exhaustive validation process to formally prove its linearity, accuracy, specificity, and robustness. While multiple researchers have engineered distinct isocratic and gradient separation schemes to analyze these compounds, a collective critical evaluation of these individual methodologies is absent from the literature. This review paper consolidates the various reported RP-HPLC, UPLC, and LC-MS/MS setups, providing a comparative analysis of their validation parameters and forced degradation resolutions. By identifying structural trends and highlighting modern shifts toward eco-friendly mobile phases, this text serves as a definitive operational roadmap for analytical scientists navigating this critical antimalarial drug combination.

II. AIM & OBJECTIVE

Aim

To develop and validate a simple, rapid, specific, precise, accurate, and robust reverse-phase high-performance liquid chromatographic method for the simultaneous estimation of Proguanil and Atovaquone in bulk drug and combined tablet dosage form in accordance with ICH guidelines.

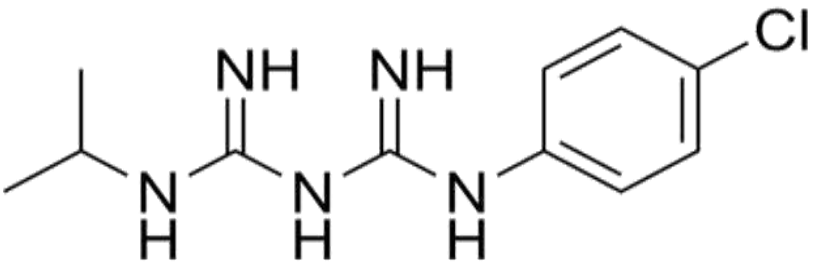
Objectives

- To select a suitable reversed-phase chromatographic column for the effective separation of Proguanil and Atovaquone.

- To optimize chromatographic conditions, including mobile-phase composition, flow rate, column temperature, injection volume, and detection wavelength
- To achieve adequate separation of Proguanil and Atovaquone with short retention times and acceptable peak symmetry.
- To establish an appropriate detection wavelength for the simultaneous determination of both drugs using a UV detector.
- To prepare standard and sample solutions of Proguanil and Atovaquone and determine their retention behaviour under optimized chromatographic conditions.
- To evaluate the linearity and range of the developed method for both analytes.
- To determine the accuracy of the method through percentage recovery studies.
- To assess the precision of the method by evaluating system precision, method precision, and intermediate precision.
- To determine the limit of detection and limit of quantitation for Proguanil and Atovaquone. To evaluate the specificity and selectivity of the method in the presence of formulation excipients.
- To assess the robustness and ruggedness of the method by making deliberate variations in chromatographic conditions.
- To evaluate solution stability and system-suitability parameters, including retention time, theoretical plates, tailing factor, resolution, and percentage relative standard deviation.

Drug Profile
Proguanil Synonym: Chloroguanide Triazine Hydrochloride
Application: An active metabolite of proguanil
CAS Number: 152-53-4
Molecular Weight: 288.18
Molecular Formula: C11H14ClN5•HCl

Structure of Proguanil



Technical Information
Physical State: Solid Solubility: Soluble in Water
Storage: Store at -20° C
Melting Point: 210-2150°C (lit.)

ISSN: 3139-8464 (p)

Indication:
For the treatment or prevention of Pneumocystis carinii pneumonia in patients who are intolerant to trimethoprim sulfamethoxazole (TMP-SMX). Also indicated for the acute oral treatment of mild to moderate PCP in patients who are intolerant to TMP-SMX.

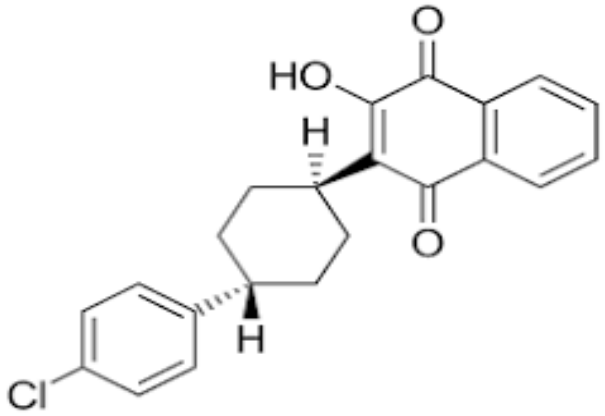
Pharmacodynamics:
Atovaquone is a highly lipophilic drug that closely resembles the structure ubiquinone. Its inhibitory effect being comparable to ubiquinone, in sensitive parasites atovaquone can act by selectively affecting mitochondrial electron transport and parallel processes such as ATP and pyrimidine biosynthesis. For illustration, cytochrome bc1 complex (complex III) seems to serve as a highly discriminating molecular target for atovaquone in Plasmodia atovaquone has the advantage of not causing myelosuppression, which is an important issue in patients who have undergone bone marrow transplantation.
Mechanism of action Atovaquone is a hydroxy- 1, 4- naphthoquinone, an analog of ubiquinone, with antipneumocystis activity. The mechanism of action against Pneumocystis carinii has not been fully elucidated. In Plasmodium species, the site of action appears to be the cytochrome bc1 complex (Complex III). Several metabolic enzymes are linked to the mitochondrial electron transport chain via ubiquinone. Inhibition of electron transport by atovaquone will result in indirect inhibition of these enzymes. The ultimate metabolic effects of such blockade may include inhibition of nucleic acid and ATP synthesis. Atovaquone also has been shown to have good in vitro activity against Toxoplasma gondii.

Absorption:
The bioavailability of atovaquone is low and variable and is highly dependent on formulation and diet. Bioavailability of the suspension increases two-fold when administered with meals. When administered with food, bioavailability is approximately 47%. Without food, the bioavailability is 23%. Volume of distribution :0.60 ± 0.17 L/kg Protein binding: Atovaquone is extensively bound to plasma proteins (99.9%) over the concentration range of 1 to 90 μg/mL. Metabolism Some evidence suggests limited metabolism (although no metabolites have been identified). Route of elimination the half-life of atovaquone is long due to presumed enterohepatic cycling and eventual fecal elimination. There was little or no excretion of atovaquone in the urine (less than 0.6%).

Half-life: 2.2 to 3.2 day
Clearance: 10.4 +/- 5.5 ml/min [HIV-infected patients receiving IV administration]
Toxicity The median lethal dose is higher than the maximum oral dose tested in mice and rats (1825 mg/kg per day). Overdoses up to 31,500 mg of atovaquone have been reported. In one such patient who also took an unspecified dose of dapsone, methemoglobinemia occurred. Rash has also been reported after overdose.
Affected organisms: Plasmodium Atovaquone
Application: An inhibitor of mitochondrial electron transport
CAS Number: 95233-18-4

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Molecular Weight: 366.84
Molecular Formula: C22H19ClO3
Structure of Atovaquone



Indication
For the treatment or prevention of Pneumocystis carinii pneumonia in patients who are intolerant to trimethoprim-sulfamethoxazole (TMPSMX). Also indicated for the acute oral treatment of mild to moderate PCP in patients who are intolerant to TMP-SMX. Pharmacodynamics Atovaquone is a highly lipophilic drug that closely resembles the structure ubiquinone. Its inhibitory effect being comparable to ubiquinone, in sensitive parasites atovaquone can act by selectively affecting mitochondrial electron transport and parallel processes such as ATP and pyrimidine biosynthesis. For illustration, cytochrome bc1 complex (complex III) seems to serve as a highly discriminating molecular target for atovaquone in Plasmodia atovaquone has the advantage of not causing myelosuppression, which is an important issue in patients who have undergone bone marrow transplantation.

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Half-life: 2.2 to 3.2 days
Clearance: 0.4 +/- 5.5 ml/min [HIV-infected patients receiving IV administration]

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III. MATERIALS AND METHODS:

3.1 Chemicals, Reagents, and Reference Standards

The reference standards and chemical inputs reviewed across contemporary literature follow stringent pharmaceutical analytical specifications:

- Active Pharmaceutical Ingredients (APIs):

High-purity reference standards (>99.5% w/w) of Atovaquone and Proguanil Hydrochloride. These are typically obtained from central regulatory repositories or pharmaceutical manufacturers (e.g., Cipla, IPCA Laboratories, or Sigma-Aldrich).

- Chromatographic Solvents:

High-purity, HPLC-grade Acetonitrile and Methanol.

- Aqueous Components and Acid Modifiers:

Ultrapure, deionized water processed via water purification systems (e.g., Milli-Q). Mobile phase pH alterations are achieved using analytical-grade reagents, including ortho-phosphoric acid (OPA), formic acid, ammonium formate, or potassium dihydrogen phosphate salts. 3.2 Chromatographic Instrumentation and Conditions
The analytical methodologies compiled in this review utilize advanced high-performance liquid chromatography systems (including Waters, Agilent, and Shimadzu configurations) equipped with the following units:

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Pumps and Injectors:
Quaternary or binary gradient delivery pumps featuring automated sample injection valves with loop capacities ranging between 10 μL and 20 μL.

- Detection Units:

Photodiode Array (PDA) or multi-wavelength Ultra-Violet (UV) spectrophotometric detectors. Spectral scanning across literature identifies a balanced absorption bandwidth between 254 nm and 287 nm to resolve the concentration asymmetry between the APIs.

- Stationary Phase Geometry:

Analytical separations are evaluated on columns of varying chemistry, primarily Octadecylsilane (C18) and Octylsilane (C8) matrices (e.g., Kromasil, Supelcosil, YMC Pack Pro). Standard structural dimensions are 150 × 4.6 mm or 250 × 4.6 mm with a particle size diameter of 5 μm. High-throughput methods shift toward sub-2-micron configurations (1.8 μm) using Ultra-Performance Liquid Chromatography (UPLC) platforms.

- Fluid Dynamics:

Eluent phase movement is driven at fixed isocratic or gradient delivery speeds ranging from 1.0 mL/min to 2.0 mL/min under ambient or controlled temperature conditions.

3.3 Preparation of Standard and Sample Solutions

3.3.1 Primary Stock Solutions

Due to the divergent solubility profile of the lipophilic Atovaquone against the polar Proguanil Hydrochloride, unified sample diluents must contain strong organic fractions to ensure comprehensive solute extraction without precipitation

- Proguanil Hydrochloride Stock:

Accurately weighing 10 mg of Proguanil Hydrochloride standard, transferring into a 100 mL volumetric flask, and dissolving with an organic diluent/mobile phase. Short-duration sonication is applied to ensure complete dissolution, yielding a final target strength of 100 μg/mL.

- Atovaquone Stock:

Accurately weighing 25 mg of Atovaquone standard, transferring into a 100 mL volumetric flask, adding an organic matrix (pure Methanol, Acetonitrile, or an organic-rich blend), and sonicating thoroughly to overcome hydrophobic resistance, adjusting to final volume to reach a concentration of 250 μg/mL.

3.3.2 Combined Working Standard Solutions

Aliquots from the respective primary standard stocks are precisely diluted using the specified mobile phase to build mixed reference standards. These working solutions are mapped to span the

asymmetric target ranges mirroring commercial doses (e.g., 50 to 150 µg/mL for Proguanil and 125 to 375 µg/mL for Atovaquone).

3.3.3 Formulation Sample Preparation (Commercial Tablets)

To determine content uniformity in commercial fixed-dose formulations (such as tablets containing 250 mg Atovaquone and 100 mg Proguanil Hydrochloride

A minimum of twenty commercial tablets is weighed independently to deduce average mass variations and then crushed into a fine composite powder.

1. A powder quantity equivalent to the weight of one tablet is accurately weighed and transferred into a clean volumetric flask.
2. Approximately 60% to 70% of the total volume is filled with sample diluent (e.g., Acetonitrile/Methanol), followed by mechanical shaking and sonication for 15 to 30 minutes to detach the active components from insoluble tablet excipients (e.g., microcrystalline cellulose, starch glycolate).
3. The extraction fluid is cooled to room temperature, diluted to volume, and passed through a 0.45 µm membrane filter to strip lingering particulates prior to chromatographic injection.

3.4 Forced Degradation (Stability-Indicating) Protocol Structure

To validate method specificity under forced stress conditions, methods are benchmarked against ICH Q1A(R2) degradation conditions.

Aliquots of the active stock formulations are exposed to chemical and environmental stressors to generate degradation products

Stress Type	Operational Reagents / Conditions	Targeted Exposure Window
Acidic Hydrolysis	0.1 M to 1.0 M Hydrochloric Acid (HCl)	Refluxed at 60°C–70°C for 1 to 3 hours
Alkaline Hydrolysis	0.1 M to 1.0 M Sodium Hydroxide (NaOH)	Refluxed at 60°C–70°C for 1 to 3 hours
Oxidative Stress	3.0% to 30.0% Hydrogen Peroxide (H_2O_2)	Ambient or thermal exposure up to 48 hours
Thermal Degradation	Dry Heat Oven (70°C to 105°C)	Continuous exposure for 24 to 72 hours
Photolytic Degradation	Short/Long UV radiation or cool white fluorescent light	Exceeded threshold of 1.2M lux hours

Following exposure, the chemically stressed samples are neutralized (where applicable), diluted to target validation strengths using mobile phase, and chromatographically profiled to evaluate the method's capability to resolve the parent drug peaks cleanly from any co-eluting degradant fragments.

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IV. RESULTS AND DISCUSSION

4.1 Evaluation of Chromatographic Performance and Resolution

The primary objective of the reviewed methodologies is achieving baseline separation (\ (R_s > 2.0\)) between the highly polar proguanil hydrochloride and the strongly lipophilic atovaquone.

- Retention Behavior:

In reversed-phase chromatography, proguanil consistently elutes first due to its affinity for the aqueous mobile phase, while atovaquone is strongly retained by the hydrophobic stationary phase.

- Peak Symmetry:

Early methods using pure unbuffered water-methanol mixtures reported significant peak tailing for proguanil (tailing factor T > 1.8) due to secondary interactions with ionized silanol groups. Modern methods resolve this by incorporating acidic modifiers (such as ortho-phosphoric acid or formic acid) to maintain an optimal system pH between 2.0 and 3.5, compressing tailing factors to a pristine range of 1.05 to 1.30.

4.2 Direct Comparison of Method Validation Benchmarks

4.2.1 Linearity Profiles and Range Correlation

As observed in the matrix table, the concentration ranges are intentionally skewed to match the typical 2.5:1 commercial formulation ratio (250 mg Atovaquone to 100 mg Proguanil). Methods such as those by Sahoo et al. and Sawant et al. capture this ratio effectively. Across all validated studies, the correlation coefficients (R^2) consistently exceed 0.999, proving excellent detector responsiveness.

4.2.2 Analytical Sensitivity (LOD & LOQ)

- Standard U/HPLC Sensitivity: Traditional RP-HPLC methods yield Limit of Detection (LOD) thresholds between 0.15 and 0.45 µg/mL.
- Advanced Particle Technology: Bhavyasri et al. utilized a sub-2-micron core-shell particle column (1.8 µm) to achieve enhanced sensitivity, reducing the LOD to <0.05 µg/mL for both compounds. This demonstrates the superior power of modern UPLC hardware for trace impurity analysis.

4.2.3 Forced Degradation Recovery and Specificity

Methods featuring stability-indicating protocols successfully map degradation paths without active ingredient interference:

- Hydrolytic Stability: Proguanil exhibits moderate degradation under intense acidic reflux, yielding small, polar biguanide-cleaved fragments that elute safely within the 1.0 to 2.0-minute void volume window.
- Oxidative and Photolytic Susceptibility: Atovaquone is susceptible to peroxide-induced structural ring changes. However, as documented by Sawant et al., utilizing a carefully optimized

mobile phase ensures that all stress-induced degradation products resolve cleanly from the active parent peaks, achieving a mass balance near 98–101%.

V. CONCLUSION:

An optimized RP-HPLC method provides a rapid and precise approach for the simultaneous estimation of Proguanil Hydrochloride and Atovaquone in tablets, featuring retention times under 2.5 minutes and high recovery rates (>99%). This high-throughput framework is well-suited for industrial quality control, with future developments focusing on green chemistry principles to enhance environmental sustainability. For more details, review the study findings on the proposed analytical method.

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ESG Reporting of Public Sector Banks: Evidence from The Bombay Stock Exchange

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***Abstract*—Environmental, Social, and Governance (ESG) reporting has emerged as a critical component of corporate transparency and sustainable business practices. This study examines the relationship between ESG reporting and financial performance in the public sector banks using evidence from companies listed on the Bombay Stock Exchange (BSE). The study uses secondary panel data of 12 major public sector banks over the period 2023–2024, comprising 24 observations. ESG scores along with their components Environmental (E), Social (S), and Governance (G) are analysed in relation to Return on Assets (ROA), along with control variables such as firm size and leverage. Regression analysis is employed to evaluate the impact of ESG factors on firm performance. The findings reveal that although the overall regression model is statistically significant, individual ESG variables do not show significant influence on financial performance. This is primarily attributed to multicollinearity among ESG components. The study contributes to the growing body of literature on ESG in emerging markets and highlights the importance of proper model specification in ESG research.**

***Index Terms*—ESG (Environmental, Social, and Governance), Financial Performance (ROA), Public Sector Bank, Sustainability Reporting, Firm Size and Leverage, Panel Data Analysis.**

I. INTRODUCTION

In recent years, ESG reporting has gained global recognition as an essential tool for evaluating corporate sustainability and ethical performance. Investors, regulators, and stakeholders increasingly rely on ESG disclosures to assess long-term risks and opportunities. ESG integrates

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environmental concerns, social responsibilities, and governance practices into corporate decision-making processes.

In India, ESG reporting has witnessed rapid growth, particularly after the introduction of the Business Responsibility and Sustainability Reporting (BRSR) framework by the Securities and Exchange Board of India (SEBI). This initiative mandates top listed companies to disclose ESG-related information in a standardized format, enhancing transparency and comparability.

The Bombay Stock Exchange, one of Asia's oldest stock exchanges, provides a diverse platform for analysing ESG practices across industries. Among these, the public sector banks hold a pivotal role in economic development, as it influences capital allocation and investment decisions.

Financial institutions, including banks and non-banking financial companies (NBFCs), are increasingly integrating ESG principles into their operations. These institutions are not only evaluated based on financial performance but also on their contribution to sustainable development.

Despite the growing importance of ESG, there remains limited empirical evidence on its impact in the Indian context, particularly within the public sector banks. This study aims to fill this gap by examining the relationship between ESG reporting and financial performance using quantitative methods.

II. LITERATURE REVIEW

1. Mishra Sashi Kanta and Suar Damodar (2010) analyzed Indian firms and found that responsible business practices positively influence firm performance through improved reputation and stakeholder trust. Their study highlights that CSR initiatives contribute indirectly to profitability by enhancing corporate image.
2. Ghosh Saptarshi (2012) examined CSR practices in Indian banks and reported that socially responsible banks tend to perform better in terms of financial stability and customer trust. The study emphasizes the role of CSR in strengthening long-term sustainability in the banking sector.
3. Chakraborty Indrani (2013) focused on corporate governance practices in Indian firms and found that strong governance mechanisms significantly improve firm valuation and operational efficiency. This aligns with global findings that governance is a key pillar of ESG performance.
4. Arora Pooja and Dharwadkar Ravi (2014) explored CSR disclosure practices and concluded that firms with higher transparency and disclosure levels tend to attract more investors and exhibit better financial outcomes.
5. Bansal Nidhi (2015) investigated sustainability reporting among Indian companies and found a gradual increase in ESG disclosures following regulatory pressure and global integration. However, the study noted inconsistencies in reporting standards across firms.
6. Kumar Satish (2016) examined the relationship between ESG indicators and financial performance and reported a positive association, particularly for governance and social factors. The study suggests that ESG adoption enhances operational efficiency and risk management.

7. Gupta Ruchi (2017) found that CSR expenditure has a significant positive impact on profitability measures such as ROA and ROE in Indian listed firms. The research highlights that strategic CSR investments contribute to long-term value creation.
8. Aggarwal Priyanka (2018) analyzed ESG disclosure practices and concluded that firms with higher ESG transparency experience better market valuation and investor confidence. The study also emphasized the importance of standardized reporting frameworks.
9. Sharma Deepak (2021) examined ESG performance of Indian firms and found a moderate positive relationship with financial performance indicators. The study indicates that ESG integration is still at a developing stage in India.
10. Kumar Vineet (2021) focused on sustainable finance and ESG integration in Indian companies, highlighting that firms adopting ESG practices demonstrate improved resilience during economic uncertainty, particularly during financial crises.
11. Verma Ankit (2022) analyzed ESG practices in Indian banking institutions and found that ESG adoption positively influences risk management and asset quality, though the impact on profitability is gradual.
12. Rao Pavan (2023) studied the impact of the Business Responsibility and Sustainability Reporting (BRSR) framework introduced by Securities and Exchange Board of India and found that it significantly improved ESG disclosure quality and comparability among Indian listed firms.

III. RESEARCH GAP

Despite the growing global literature on Environmental, Social, and Governance (ESG) practices, research in the Indian public sector banks remains limited. Most Indian studies primarily focus on Corporate Social Responsibility (CSR) rather than a comprehensive ESG framework integrating environmental, social, and governance dimensions. Financial service firms listed on the Bombay Stock Exchange possess unique characteristics such as high leverage, strict regulatory compliance, and systemic importance, requiring sector-specific ESG analysis that remains underexplored.
Another major limitation is the lack of long-term panel data analysis. Existing studies often use cross-sectional or short-term data, limiting the understanding of dynamic relationships between ESG performance and financial outcomes. Furthermore, many studies inadequately address econometric challenges such as multicollinearity among ESG variables, which may distort regression estimates and reduce result reliability.

To address these gaps, the present study employs a structured panel dataset of selected financial service firms during 2023–2024. The study adopts a comprehensive ESG framework, incorporates firm-specific control variables, and applies rigorous econometric techniques including multicollinearity diagnostics to ensure robust and reliable findings. The research contributes to the emerging ESG literature in India by examining the relationship between sustainability practices and financial performance in the public sector banks.

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IV. OBJECTIVES OF THE STUDY

1.To analyze ESG reporting practices of public sector banks listed on the Bombay Stock Exchange.
2.To examine the relationship between ESG scores and financial performance.
3.To evaluate the impact of individual ESG components on firm performance.

V. HYPOTHESES

1.H1: ESG score has a significant impact on firm performance.
2.H2: Environmental factors significantly influence ROA.
3.H3: Social and Governance factors affect profitability.

VI. RESEARCH METHODOLOGY

The research methodology adopted for thus research paper is descriptive and analytical in nature. Which outlines the systematic approach adopted to achieve the objectives of the study. It includes the data sources, sample design, and overall framework used for analysing the relationship between ESG performance and financial outcomes in the public sector banks.

6.1 Data Source

For this research data has been collected from CRISIL Rating and Business Responsibility and Sustainability Reporting with public sectors banks listed in BSE.

6.2 Sample Design

The sample design plays a crucial role in ensuring that the study results are representative and relevant to the public sector banks.

The study selects a sample of 12 public sector banks listed on the Bombay Stock Exchange. These companies are chosen based on their market capitalization, ensuring that only large and actively traded firms are included. This approach enhances the reliability of ESG disclosures, as larger firms tend to have better reporting practices and higher regulatory compliance.

The study covers a time period of 02 years (2023–2024), enabling a comprehensive analysis of trends and patterns over time. This longitudinal framework allows for better understanding of how ESG practices evolve and influence financial performance in the long run.

The total number of observations in the study is 24, derived from 12 banks over 02 years. This panel dataset combines both cross-sectional (different firms) and time-series (multiple years) dimensions, making it suitable for advanced statistical analysis such as regression modelling.

A purposive sampling method is employed, where firms are selected intentionally based on specific criteria namely, their size (market capitalization) and availability of consistent ESG and financial data. This method ensures that the sample is relevant to the research objectives, although it may limit generalizability to smaller firms or other sectors.

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6.3 Variables considered for the Study

To examine the relationship between ESG performance and financial outcomes, the study uses dependent, independent, and control variables. Return on Assets (ROA) is used as the dependent variable to measure financial performance and operational efficiency. The independent variable is the ESG score, which represents the overall sustainability performance of a firm based on Environmental (E), Social (S), and Governance (G) dimensions. Environmental factors include carbon emissions and energy efficiency, social factors include employee and community relations, while governance focuses on transparency, accountability, and board practices.

The study also includes control variables to improve the accuracy of the analysis. Firm Size (SIZE), measured using the natural logarithm of total assets, captures the influence of organizational scale and resource availability. Leverage (LEV), measured as the ratio of total debt to total assets and represents the financial risk associated with debt financing. These variables help explain variations in financial performance among financial service firms listed on the Bombay Stock Exchange.

Table 1: Summary of Variables

Type	Variables	Measurement
Dependent	ROA	Net Profit / Total Assets
Independent	ESG	(E + S + G) / 3
	E, S, G	Individual ESG components
Control	SIZE	ln (Total Assets)
	LEV	Total Debt / Total Assets

Source: Created by authors

6.4 Model Specification

To examine the impact of Environmental, Social, and Governance (ESG) performance on financial outcomes, the study employs a multiple regression model. The model is designed to analyze the relationship between ESG scores and firm performance while controlling for firm-specific characteristics such as size and leverage. The analysis focuses on public sector banks listed on the Bombay Stock Exchange.

The baseline regression model used in the study is specified as follows:

$ROA=\beta 0+\beta 1ESG+\beta 2SIZE+\beta 3LEV+\epsilon$

Explanation of Variables

- ROA (Return on Assets): The dependent variable representing the financial performance of the firm.
- β_0 (Intercept): The constant term, indicating the expected value of ROA when all independent variables are equal to zero.
- ESG: The composite ESG score, representing the overall sustainability performance of the firm.
- SIZE: Firm size measured as the natural logarithm of total assets, included to control for the effect of scale.

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- LEV (Leverage): The ratio of total debt to total assets, included to account for financial risk.
- ε (Error Term): The disturbance term capturing the effect of other variables not included in the model.

VII. DATA ANALYSIS AND RESULTS

➢ Relationship between ESG and ROA

Model:

$ROA=\beta0+\beta1(ESG) +\beta2(Size) +\varepsilon$

From your uploaded dataset, the fitted model gives:

Statistic	Value
R^2	0.1320
Model p-value	0.2261

Estimated coefficients:

Variable	Coefficient	p-value
Constant	-0.01189	0.293
ESG Score	0.000260	0.185
Firm Size	0.000293	0.627

Interpretation:

The regression model explains 13.2% of the variation in ROA. The results show that ESG Score and Firm Size are not statistically significant at the 5% level. Although the ESG coefficient is positive, indicating that higher ESG scores are associated with higher ROA, the relationship is not statistically significant. Therefore, there is insufficient evidence to conclude that ESG performance has a significant effect on ROA.

➢ Impact of Environmental, Social and Governance on ROA

Model:

$ROA=\beta0+\beta1(E) +\beta2(S) +\beta3(G) +\beta4(Size) +\varepsilon$

For this objective, report:

Model Summary

- ANOVA
- Coefficient Table
- Hypothesis Testing
- Interpretation

ESG reporting practices of public sector banks listed on the Bombay Stock Exchange

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Table 2: Descriptive Statistics of ESG Variables (n = 24)

ESG Variable	Mean	Standard Deviation	Minimum	Maximum
Environmental (E)	54.75	3.90	47	61
Social (S)	63.42	3.60	56	71
Governance (G)	62.08	4.60	54	71
Overall ESG Score	60.29	3.18	55	67

Source: Computed from the study data.

Interpretation

The descriptive statistics indicate that the selected public sector banks maintain a relatively consistent level of ESG reporting. The overall ESG score averaged 60.29, with a standard deviation of 3.18, suggesting limited variation across banks and years.

Among the three ESG dimensions, the social pillar recorded the highest average score (63.42), followed by the Governance pillar (62.08). The Environmental pillar had the lowest mean score (54.75), indicating comparatively lower environmental disclosure and performance.

The Environmental scores ranged from 47 to 61, whereas the Social and Governance scores ranged from 56–71 and 54–71, respectively. These findings suggest that the sampled public sector banks have placed relatively greater emphasis on social and governance initiatives than on environmental practices during the study period.

Table 3: Mean ESG Scores by Year

Variable	2023	2024	Change
Environmental	53.75	55.75	+2.00
Social	63.33	63.50	+0.17
Governance	62.50	61.67	−0.83
ESG Score	60.50	60.08	−0.42

Interpretation

Between 2023 and 2024, the average Environmental score increased by 2.00 points, reflecting an improvement in environmental practices among the sampled public sector banks. The Social dimension remained relatively stable, while the Governance score showed a slight decline. The overall ESG score remained broadly stable across the two years, indicating consistency in sustainability reporting despite modest changes in individual ESG dimensions.

The relationship between ESG scores and financial performance (measured using Return on Assets)

Table 4: Pearson Correlation Matrix

Variables	ESG Score	ROA	Firm Size
ESG Score	1.000	0.349	0.405
ROA	0.349	1.000	0.233
Firm Size	0.405	0.233	1.000

Source: Computed from the study data (n = 24).

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Interpretation

The Pearson correlation analysis indicates a moderate positive correlation between ESG Score and ROA (r = 0.349), suggesting that banks with higher ESG scores tend to report slightly higher returns on assets. ESG Score also shows a moderate positive relationship with Firm Size (r = 0.405). The correlation between Firm Size and ROA (r = 0.233) is weak and positive. The correlation coefficients do not indicate severe multicollinearity among the variables.

Table 5. Regression Model Summary

Statistic	Value
Dependent Variable	ROA
Independent Variable	ESG Score
Control Variable	Firm Size
Observations	24
R^2	0.132
Adjusted R^2	0.049 *(approx.)*
Model Significance (p-value)	0.226

Table 6: Regression Coefficients

Variable	Coefficient (β)	p-value	Decision
Constant	-0.01189	0.293	Not Significant
ESG Score	0.000260	0.185	Not Significant
Firm Size	0.000293	0.627	Not Significant

Regression Model

$ROA=\beta0+\beta1(ESG) +\beta2(Size) +\varepsilon$

Estimated equation:

$ROA=-0.01189+0.000260(ESG) +0.000293(Size)$

Interpretation

The regression model explains 13.2% of the variation in ROA (R^2 = 0.132), indicating limited explanatory power. The overall model is not statistically significant (p = 0.226), suggesting that the combination of ESG Score and Firm Size does not significantly predict ROA for the sampled public sector banks.

The estimated coefficient for ESG Score (β = 0.000260) is positive, indicating that higher ESG scores are associated with a marginal increase in ROA. However, this relationship is not statistically significant (p = 0.185). Likewise, Firm Size exhibits a positive but statistically insignificant coefficient (p = 0.627). These findings suggest that ESG performance is positively associated with financial performance in direction, but the evidence from this sample is insufficient to conclude that ESG has a statistically significant effect on ROA.

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Table 7: Hypothesis Testing

Hypothesis	Result
H_0: ESG Score has no significant effect on ROA	Fail to Reject H_0
H_1: ESG Score has a significant effect on ROA	Rejected

Conclusion

Within the present sample of 12 public sector banks observed over two years, ESG Score does not have a statistically significant effect on Return on Assets. Although the estimated relationship is positive, the available evidence indicates that ESG reporting alone does not explain a substantial proportion of the variation in financial performance.

Regression Model:

$ROA=\beta0+\beta1(E) +\beta2(S) +\beta3(G) +\beta4(Size) +\varepsilon$

Table 8: Model Summary

Particulars	Value
Multiple R	0.4699
R Square	0.2208
Adjusted R Square	0.1039
Standard Error	0.04885
Observations	24

Source: Computed from the study data.

Interpretation

The regression model produced a Multiple R value of 0.4699, indicating a moderate positive relationship between the predicted and observed ROA values. The coefficient of determination (R^2 = 0.2208) shows that 22.08% of the variation in ROA is explained by the Environmental, Social, and Governance variables. The adjusted R^2 of 0.1039 indicates relatively low explanatory power after accounting for the number of predictors.

Table 9: ANOVA

Source	df	SS	MS	F	p-value
Regression	3	0.013523	0.004508	1.8889	0.1640
Residual	20	0.047727	0.002386		
Total	23	0.061250			

Interpretation

The ANOVA results indicate that the regression model is not statistically significant (F = 1.8889, p = 0.1640). Therefore, the Environmental, Social, and Governance variables, when considered jointly, do not significantly explain the variation in ROA among the selected public sector banks.

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Table 10: Regression Coefficients

Variable	Coefficient (β)	Std. Error	t-value	p-value	Decision
Constant	-0.3779	0.2141	-1.7650	0.0928	Not Significant
Environmental	0.0043	0.0031	1.3986	0.1773	Not Significant
Social	0.0022	0.0037	0.5902	0.5617	Not Significant
Governance	0.0019	0.0026	0.7347	0.4710	Not Significant

Estimated Regression Equation

$ROA = -0.3779 + 0.0043(E) + 0.0022(S) + 0.0019(G)$

Interpretation of Regression Coefficients

Environmental

The Environmental coefficient ($\beta = 0.0043$) is positive, indicating that higher environmental performance is associated with a slight increase in ROA. However, the relationship is not statistically significant ($p = 0.1773$).

Social

The Social coefficient ($\beta = 0.0022$) is also positive, indicating a positive association with ROA. However, the coefficient is not statistically significant ($p = 0.5617$).

Governance

The Governance coefficient ($\beta = 0.0019$) indicates a positive relationship with ROA, but the association is not statistically significant ($p = 0.4710$).

Table 11: Hypothesis Testing

Hypothesis	p-value	Decision
H_{01}: Environmental has no significant effect on ROA	0.1773	Fail to Reject H_0
H_{02}: Social has no significant effect on ROA	0.5617	Fail to Reject H_0
H_{03}: Governance has no significant effect on ROA	0.4710	Fail to Reject H_0

Objective-wise Interpretation

The multiple regression analysis indicates that all three ESG dimensions have positive coefficients, suggesting that improvements in Environmental, Social, and Governance performance are associated with increases in ROA. However, none of these effects are statistically significant at the 5% significance level.

The overall regression model is also not statistically significant, indicating that the selected ESG dimensions do not collectively explain a statistically significant proportion of the variation in ROA within the study period.

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Among the three ESG dimensions, the Environmental score exhibits the largest estimated coefficient, followed by the Social and Governance scores. While these positive coefficients indicate a favourable directional association with financial performance, the evidence from the present sample is insufficient to conclude that improvements in individual ESG dimensions translate into significant improvements in ROA.

VIII. FINDINGS

- The selected public sector banks exhibited a moderate level of ESG performance during the study period, with an average ESG score of approximately 60.29, indicating consistent adoption of ESG reporting practices.
- Among the three ESG dimensions, the social component recorded the highest average score, followed by Governance, while the Environmental component recorded the lowest average score, indicating comparatively lower emphasis on environmental initiatives.
- The year-wise analysis showed only marginal changes in ESG scores between 2023 and 2024, suggesting that ESG reporting practices remained relatively stable during the study period.
- The correlation analysis indicated a positive association between ESG performance and financial performance (ROA), implying that banks with relatively higher ESG scores generally reported better profitability.
- The regression analysis examining the relationship between overall ESG Score and ROA indicated a positive regression coefficient, suggesting that improvements in ESG performance were associated with increases in ROA. However, the relationship was not statistically significant at the 5% significance level.
- The regression model incorporating the Environmental, Social, and Governance dimensions explained approximately 22.08% of the variation in ROA, indicating that ESG dimensions accounted for only a modest proportion of differences in financial performance among the sampled banks.
- All three ESG dimensions (Environmental, Social, and Governance) exhibited positive regression coefficients, indicating favourable directional relationships with financial performance. However, none of the coefficients were statistically significant, indicating insufficient evidence to establish a significant individual impact on ROA.
- The Environmental dimension recorded the highest regression coefficient among the three ESG components, suggesting that improvements in environmental performance were associated with relatively greater increases in ROA than the Social and Governance dimensions, although this relationship was not statistically significant.
- The overall regression models were not statistically significant, indicating that ESG variables alone did not provide sufficient explanatory power to predict financial performance within the selected sample of public sector banks.
- The findings suggest that financial performance in public sector banks is likely influenced by additional financial, operational, and institutional factors beyond ESG performance.

IX. SUGGESTIONS

- Public sector banks should strengthen ESG implementation, particularly environmental initiatives, as the environmental dimension showed comparatively lower performance than the social and governance dimensions.
- Banks should integrate ESG objectives into their long-term business strategies instead of treating ESG reporting merely as a regulatory compliance requirement, thereby improving its contribution to financial performance.
- Management should regularly monitor ESG performance using measurable indicators and incorporate ESG metrics into strategic planning and performance evaluation systems to enhance accountability and continuous improvement.
- Policymakers and regulatory authorities should continue promoting standardized ESG reporting frameworks to improve transparency, consistency, and comparability across public sector banks.

X. CONCLUSION

The study demonstrates that public sector banks have established a moderate level of ESG reporting, with stronger performance in the Social and Governance dimensions than in the Environmental dimension. Although the empirical analysis identified positive directional relationships between ESG performance and financial performance, these relationships were not statistically significant within the study period. The findings indicate that ESG practices alone are insufficient to explain variations in profitability and that financial performance is influenced by multiple organisational and economic factors. Continued enhancement of ESG practices, combined with improvements in financial and operational efficiency, may strengthen sustainable performance over the long term.

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Integrating Siddha Pathology in Public Health – A Review Article

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***Abstract*—Background: Siddha medicine, an ancient Dravidian system, views health as an equilibrium of the five elements and three humors (Mukkutram). Amid the rise of non-communicable diseases and recent pandemic challenges, Siddha's holistic pathological framework (Noi Naadal) offers significant potential for integrated, proactive public health strategies. Objective: This review analyzes Siddha diagnostic methodologies—specifically Envagai Thervu (eight-fold assessment), Manikadai Nool (wrist circummetric sign), and Maruthuva Jothidam (medical astrology)—and evaluates their integration into modern healthcare systems and policy frameworks. Methods: Classical literature, government reports, and peer-reviewed studies (2014–2025) were synthesized from databases like PubMed and the Ayush Research Portal. The review follows National Health Policy 2017 principles, evaluating traditional epistemology alongside modern clinical data and policy documents. Results: Siddha diagnostics provide non-invasive screening tools; studies link specific Manikadai Nool measurements (10–10.75 finger breadths) to cardiac and uterine conditions, while Neikkuri (oil drop test) correlates significantly with metabolic derangements. Although Siddha services are co-located in 13,000+ Indian facilities, challenges remain regarding standardization and professional resistance, despite high utilization (88.2%) among practitioners.**
Conclusion: Siddha pathology offers a robust, cost-effective framework for community-level chronic disease management. Global sustainability depends on rigorous standardization, digital integration via the Ayush Grid, and translating humeral theories into biophysical evidence to bridge the gap between traditional wisdom and modern clinical practice.

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***Index Terms*—Siddha Pathology; Envagai Thervu; Manikadai Nool; Public Health Integration; Naadi; Neikkuri; Mukkutram; Chronomedicine; Ayush Policy; Preventive Healthcare.**

I. INTRODUCTION

The evolution of global healthcare is increasingly defined by a shift toward integrative medicine, where the wisdom of traditional systems is synthesized with the precision of modern biomedicine. In this landscape, the Siddha system of medicine, originating in the southern part of the Indian subcontinent, offers a sophisticated understanding of health and disease that predates modern epidemiology by millennia. Siddha pathology, or Noi Naadal, is built upon the foundational belief that the universe and the human body are intertwined through the five primary elements (Aim boodham) and the three governing humors (Uyir Thathukkal). This systemic view allows Siddha to address not just the symptoms of a disease, but the fundamental imbalance of life forces that leads to pathological states.

As India faces a "quadruple burden" of disease—comprising non-communicable diseases, persisting communicable diseases, maternal and child health challenges, and an aging population—the existing biomedical infrastructure is often stretched to its limits. Siddha's focus on primordial prevention through Kayakarpam (rejuvenation) and its emphasis on individualized diet and lifestyle regimens (Pathiyam) provide a vital resource for community-level health promotion. The diagnostic methodology of Siddha, characterized by the "Eight-fold Assessment" (Envagai Thervu), allows for rapid, bedside evaluation of a patient's health status, which is particularly beneficial in rural and underserved areas.

The integration process, championed by the Ministry of Ayush since 2014, has moved traditional medicine from the periphery to the core of India's National Health Mission. This involves the co-location of Siddha practitioners in primary and community health centers and the establishment of Ayushman Arogya Mandirs.

However, the path to full integration is fraught with challenges, ranging from legal and ethical debates over "mixopathy" to the technical difficulties of standardizing ancient diagnostic techniques. This review serves to bridge the gap between tradition and science, exploring how the unique parameters of Siddha pathology can be validated and utilized to improve the quality of life and health outcomes for the public.

Envagai Thervu: The Eight-fold Assessment of Siddha Pathology

The fundamental diagnostic protocol in Siddha medicine is the Envagai Thervu, a systematic eight-fold examination that allows the physician to ascertain the nature, site, and prognosis of a disease. Sage Theraiyar defined these eight parameters as Naadi (Pulse), Sparisam (Touch), Naa (Tongue), Niram (Color), Mozhi (Speech), Vizhi (Eye), Malam (Stools), and Moothiram (Urine).

Naadi (Pulse Diagnosis)

Naadi is considered the most significant of the eight examinations, serving as the "pathfinder" for all ailments. It reflects the status of the three humors Vali, Azhal, and Iyyam at the radial artery. In the clinical setting, the physician uses three fingers (index, middle, and ring) to palpate the radial pulse, usually on the right hand for males and the left hand for females.

Finger	Humor Representation	Clinical Significance
Index	Vali (Vatham)	Reflects nervous system and musculoskeletal status
Middle	Azhal (Pitham)	Reflects metabolic, digestive, and inflammatory status
Ring	Iyyam (Kapham)	Reflects respiratory, structural, and fluid balance

Traditional texts describe the movements of these humors using animal analogies: Vatha moves like a swan or hen, Pitha like a frog or bird, and Kapha like a snake or peacock. Modern research has begun to correlate these qualitative gati with quantitative parameters such as Pulse Wave Velocity (PWV) and Heart Rate Variability (HRV). While pulse rate is a quantitative measure, Naadi is a qualitative assessment of the pulse's stability (sthiratva), speed (vega), and hardness (kathinya). Digital tools like Nadi Tarangini are currently being used to capture these subtle wave variations, providing a bridge between traditional palpation and modern physiological monitoring.

Naa (Tongue Examination)

The examination of the tongue is a vital diagnostic marker in Siddha, particularly for gastrointestinal disorders (Gunmam) and metabolic status. The physician observes the color, surface coating, moisture levels, movement, and taste sensation.

- Vatha diseases: The tongue may appear black or blue, often with dryness or a rough surface.
- Pitha diseases: The tongue typically appears red or yellowish, sometimes with a greenish tinge or inflammatory signs.
- Kapha diseases: The tongue is often pale, white, or covered with a thick, frothy coating.

In conditions such as Sirakkamba vatham (cerebrovascular accident), deviations in tongue movement and speech can help in identifying the posterior circulation involvement. Tongue examination also provides clues to systemic toxicity; for instance, a bitter taste sensation may be used to identify specific snake bites in traditional toxicological management.

Niram (Body Color and Complexion)

Examination of Niram involves observing the color of the skin, nails, hair, conjunctiva, and mucous membranes. This parameter provides a macro-level view of the patient’s constitutional type and current pathological state.

Observation Site	Pathological Indicator	Humor Association
Skin	Blackish/Dark discoloration	Vatha derangement
Face/Oral Cavity	Yellowish tint	Pitha derangement (e.g., jaundice)

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Observation Site	Pathological Indicator	Humor Association
Face	Pallor/White tint	Kapha derangement (e.g., anemia)
Conjunctiva	Muddy/Watery/Painful	Vatha involvement
Conjunctiva	Greenish-red/Effusion	Pitha involvement (e.g., hemorrhagic)

Siddha texts also link complexion to planetary influences, suggesting that the body's radiance can change in the months leading up to death, a concept used in terminal care prognosis.

Mozhi (Speech and Voice)

The quality of speech (Mozhi) is assessed for tone, clarity, and articulation. Changes in voice provide direct evidence of humeral vitiation in the vocal cords and the respiratory tract.

- Vatha diseases: Characterized by a "samana saptam" (normal but potentially slurred or inarticulate) voice.
- Pitha diseases: Often results in a high-pitched, shrill, or aggressive voice.
- Kapha diseases: Results in a low-pitched, resonant, or hoarse voice, often due to phlegm accumulation.

Mozhi is also critical in neurological assessments, where aphasia (expressive or comprehensive) or dysphonia can indicate specific brain lesions or strokes.

Vizhi (Eye Examination)

The eyes are considered a mirror to the body's internal health. Practitioners examine the color of the sclera, the clarity of the cornea, pupillary response, and the condition of the eyelids.

- Vatha signs: Dryness (exophthalmos), Bitot’s spots, and increased lacrimation.
- Pitha signs: yellowish sclera (Kamalai/Jaundice), burning sensations, and redness.
- Kapha signs: Pale conjunctiva, opacity (cataracts), and thick eye discharges.

In modern Siddha practice, eye examination is being integrated into public health screening for conditions like diabetic retinopathy, where traditional indicators are paired with AI-enabled screening tools.

Sparisam (Touch and Palpation)

Through Sparisam, the physician assesses skin temperature, texture, and sensitivity. Palpation is used to identify tenderness, abnormal growths, macules, papules, or ulcers. In critical care, Sparisam is used to assess peripheral nervous function; for instance, cold extremities in a patient with hyperpyrexia may indicate a terminal collapse of the vital humors.

- Vatha skin: Cold, dry, and rough.
- Pitha skin: Warm, moist, and potentially inflamed.
- Kapha skin: Smooth, oily, and thick.

Malam (Stool Examination)

The nature of stools (Malam)—whether solid, liquid, or semi-solid—as well as its color and odor, provides essential information on the patient’s digestive fire (Agni) and the presence of undigested matter.

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Stool Characteristic	Pathological Inference
Constipated/Hard	Vatha derangement; dehydration
Yellow/Greenish	Pitha derangement; bile involvement
White/Frothy/Mucoid	Kapha derangement; intestinal malabsorption
Presence of occult blood	Inflammatory bowel conditions or hemorrhoids

In Gunmam (peptic ulcer) patients, stool examination is critical for identifying bleeding and digestive efficiency, with studies showing a high prevalence of specific dietary patterns contributing to these pathologies.

Moothiram (Urine Analysis: Neerkuri and Neikkuri)

Urine examination is perhaps the most scientifically validated aspect of Envagai Thervu. It is divided into two parts: Neerkuri (observation of physical properties) and Neikkuri (the oil-drop test).

Neerkuri (Physical Parameters):

The physician observes the color, smell, density, and quantity of urine collected early in the morning.

- Vatha urine: Clear white, sometimes with a slight blue tinge.
- Pitha urine: Reddish or yellowish, with high density and strong odor.
- Kapha urine: Pale white, frothy, and slow-moving.

Neikkuri (Oil Drop Test):

A drop of gingelly oil is placed on the surface of the urine using a standard dropper. The way the oil spreads determines the prognosis.

Spread Pattern	Humor Association	Prognosis
Snake-like	Vatham	Curable, but requires specific management
Ring-like	Pitham	Curable; indicates metabolic heat
Pearl-like	Kapham	Curable; indicates structural/fluid issues
Sieve-like	Kapham (severe)	Requires immediate, intensive treatment
Sinking/Mixing	Thirithodam (Mixed)	Bad prognosis; potentially incurable

Biophysical analysis suggests that the spread pattern is influenced by surface-active molecules and metabolites in the urine.

The direction of oil spreading may even be explained by paramagnetic molecules aligning with the earth's electromagnetic field. Clinical trials in PCOS patients have shown significant correlations between these patterns and the patient's hormonal status, validating the test's utility as a non-invasive screening tool.

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Manikadai Nool: The Wrist Circummetric Sign

Manikadai Nool is a specialized diagnostic and prognostic tool unique to the Siddha system, explained in classical texts like *Agasthiyar Soodamani Kajiru Soothiram*.

It involves measuring the circumference of the patient's distal forearm (wrist) using an inelastic thread and then dividing that length by the patient's own finger breadth (Viralkadai or finger breadths).

II. METHODOLOGY OF MEASUREMENT

The procedure is highly standardized:

1. Marking: A point four finger breadths away from the wrist crease is identified.
2. Circumference: An inelastic cotton thread is wrapped around the forearm at this marked level to measure the girth.
3. Calculation: The length of the thread is measured against the width of the patient's four fingers (excluding the thumb). This is then converted into units of finger breadths.
4. Inference: The resulting value (ranging from 4 to 11 fbs) is mapped to specific disease conditions and prognostic outcomes.

Clinical and Prognostic Values

The Manikadai Nool value acts as a vital indicator of the body's internal state, reflecting both physical tissues (Udal Thathukkal) and vital humors.

Measurement (fbs)	Clinical Condition and Symptoms	Prognosis
11.0	Healthy individual; good body build; long life expectancy	Excellent
10.0	Pricking pain in chest and limbs; gastritis and ulcers	Good
9.5	Edema; increased body heat; burning sensation in eyes; fever; anorexia	Fair
9.0	Impaired hearing; pain around the waist and thighs; inability to walk	Guarded
8.5	Leucorrhoea; venereal disorders; primary infertility	Guarded
8.0	Gas collection in abdomen; indigestion; weakness; pain in throat	Guarded
7.5	Osteoporosis; burning eyes; joint pain; increased temperature	Poor
6.0	Tuberculosis; severe phlegm in the chest	Bad (Death sign)
5.75	Sanni (delirium); giddiness; breathlessness; death occurs within days	Terminal
4.5	Edema; shrunken eyes; death occurs within 9 days	Terminal
4.0	Pedal edema; dark face; weakness; death occurs within 5 days	Terminal

Recent studies have validated the diagnostic significance of Manikadai Nool in specific populations. For instance, in patients with polycystic ovarian syndrome (PCOS/Soodhagavaayu), values typically fell within the 9 to 9.75 fbs range, correlating significantly with clinical symptoms like obesity and menstrual abnormalities. Another study found that values in the 10 to 10.75 fbs range were indicative of cardiac diseases and uterine fibroids.

The advancement of IoT has led to the creation of handheld, portable Manikadai measurement tools that use encoders and sensors to transmit data to mobile applications. This modernization allows for seamless data logging and historical analysis of a patient's health.

Maruthuva Jothidam: The Role of Medical Astrology and Chronobiology

Siddha medicine incorporates the concept of chronobiology the study of biological rhythms into its core pathological framework. Maruthuva Jothidam (Medical Astrology) and Kaala Ozhukam (Seasonal Regimen) are used to understand how temporal and cosmic factors influence humoral balance.

Chronobiology and Seasonal Variation (Kaala Ozhukam)

Siddha practitioners categorize the year into six seasons (Perumpozhuthu) and the day into six parts (Sirupozhuthu). The humors Vatha, Pitha, and Kapha undergo natural cycles of accumulation (Chaya), aggravation (Prakopa), and pacification (Prasama) according to these timeframes.

Season	Time Period	Humor State	Public Health Implication
Kaar (Monsoon)	Mid-Aug to Mid-Oct	Vatha vitiates; Pitha increases	Increased risk of inflammatory and skin disorders
Koothir (Autumn)	Mid-Oct to Mid-Dec	Pitha aggravates	Prevalence of digestive and bile-related disorders
Munpani (Early Winter)	Mid-Dec to Mid-Feb	Humors stabilize	Period of optimal health; good for rejuvenation
Pinpani (Late Winter)	Mid-Feb to Mid-Apr	Iyyam starts to liquefy	Onset of respiratory ailments
Illavenil (Spring)	Mid-Apr to Mid-Jun	Iyyam aggravates	High incidence of phlegmatic and allergic conditions
Muthuvenil (Summer)	Mid-Jun to Mid-Aug	Pitha increases	Risk of dehydration and heat-related stress

The system advises specific seasonal regimens (Ruthu Sariyai) to mitigate these risks. For example, during the Kaar season, it is recommended to consume sweet and sour foods mixed with honey and to avoid daytime naps to prevent Vatha vitiation.

This chronotherapeutic approach aligns with modern medicine’s understanding that cardiac events and asthma attacks often follow predictable temporal patterns.

Medical Astrology (Maruthuva Sothidaviyal)

Medical astrology is an integral branch of Siddha pathology used to ascertain a patient's physiological and psychological weaknesses based on their birth chart (natal horoscope).

Raasi and Anatomical Correlations: Each of the 12 zodiac signs (Raasis) is associated with specific anatomical locations and disease predilections.

- Mesham (Aries): Head and eyes.
- Katagam (Cancer): Stomach, breasts, and diaphragm.
- Simmam (Leo): Heart and spinal column.
- Thulam (Libra): Kidneys, lumbar vertebrae, and skin.
- Magaram (Capricorn): Knees, body joints, and hair.

The 6th house in a natal chart is considered the "house of diseases." If the 6th house falls in a particular Raasi, the individual is predicted to be vulnerable to diseases associated with that sign's body parts. Furthermore, male Raasis are linked to fast-spreading, acute diseases, while female Raasis relate to silent, aggressive, and chronic conditions. The movement nature of Raasis (Sara/Movable, Sthira/Fixed, Ubaya/Dual) also determines whether a disease will be acute, chronic, or recurrent.

Clinical trials at the National Institute of Siddha have used the Pancha Patchi Sasthiram (Five Bird Theory) retrospectively to identify and rule out conditions such as primary infertility (Maladu) and diabetes mellitus (Madhumegam) based on the time of consultation.

Integrating Siddha Pathology into Public Health

The integration of Siddha medicine into the public health system in India is a strategic effort to enhance primary healthcare (PHC) and address the rising burden of non-communicable diseases (NCDs). The National Ayush Mission (NAM), launched in 2014, serves as the primary vehicle for this integration.

Clinical Integration Models and Public Health Role

There are four primary models through which Siddha is integrated into the national health framework:

1. Co-location Model: Siddha practitioners work within conventional PHCs and District Hospitals, offering patients a choice of systems under one roof. Over 13,000 such facilities exist currently.
2. Referral-Based Model: Modern biomedical practitioners refer patients to Siddha specialists for chronic disease management or palliation.
3. Fully Integrated Services: Centers of excellence, like the National Institute of Siddha (NIS), collaborate with modern research institutes (e.g., ICMR) for clinical trials and joint health programs.
4. Parallel Model: Community-based healers and private Siddha enterprises provide care independently but are increasingly being brought under regulatory oversight.

III. KEY AREAS OF IMPACT:

- NCD Management:

Siddha's focus on metabolic equilibrium makes it highly effective for chronic conditions like diabetes, hypertension, and arthritis. Integrated NCD clinics are already operational in several government hospitals.

- Geriatric Care:

Rejuvenation practices (Kayakarpam) are utilized to manage age-related degenerative conditions like osteoporosis and Alzheimer's disease.

- Oral Health:

Siddha interventions such as oil pulling and herbal mouthwashes are being explored for integration into national oral health strategies and school programs.

- Epidemic Response:

During the COVID-19 pandemic, 46 Siddha COVID Care Centers (SCCCs) were established in Tamil Nadu, treating over 15,000 patients with a holistic approach that included Siddha medicine, dietary interventions, and psychological support.

IV. POLICY AND REGULATORY FRAMEWORK

The integration of Siddha is guided by the National Health Policy 2017, which promotes "medical pluralism"—the coexistence and integration of multiple healthcare systems. Recent advances include:

- ICD-11 Inclusion: Ayush systems are being integrated into global medical classifications.
- Insurance Coverage: Siddha treatments are increasingly covered under national insurance schemes like PM-JAY and various private insurers.
- Standardization: The Central Council for Research in Siddha (CCRS) is working to obtain NABH and NABL certifications for research institutes to ensure quality and credibility.

In Tamil Nadu, a landmark Memorandum of Understanding (MoU) was signed on July 16, 2025, between the Directorate of Public Health (DPHPM), the Commissionerate of Indian Medicine (CIM&H), and the NIS. This partnership aims to bridge the strengths of modern and traditional systems through scientific evidence generation, joint implementation of health programs, and enhanced public health research.

Policy Gaps and Regulatory Hurdles

Despite significant progress, the integration of Siddha into public health faces persistent barriers that hinder its full potential.

1.Professional Resistance and the "Mixopathy" Debate:
Many modern medical associations oppose integration, labeling it as a regressive step toward "pseudo-scientific" practices.
Concerns center on the lack of a scientific basis for integrated medicine and the fear of patient confusion in mixed settings.

2.Standardization and Evidence Gaps:
While ancient texts provide detailed diagnostic frameworks, there is a lack of large-scale scientific validation for many Siddha modalities. Standardization of formulations and diagnostic tools like Neikkuri is crucial for reproducibility and global acceptance.

3.Legal and Ethical Issues:
Conflicts exist over the legal scope of practice. While some states allow traditional practitioners to prescribe modern medicine under specific rules (e.g., Rule 2(ee)), this is frequently challenged in courts, creating a climate of legal ambiguity.

4.Educational and Infrastructure Gaps:
Ayush curricula often lack the systematic, evidence-based clinical training found in modern medicine, leading to skill gaps in emergency management. Furthermore, many traditional colleges suffer from faculty shortages and inadequate facilities.

5.Intellectual Property and Biopiracy:
The protection of indigenous Siddha knowledge from commercial exploitation is a significant concern. Lacunae in IP protection and the loss of knowledge due to the lack of documentation are persistent issues.

V. FUTURE PERSPECTIVE

The transformation of Siddha pathology from a traditional art to a modern public health tool requires a focus on innovation and global collaboration.

- Digital Health and AI:

The deployment of AI-enabled tools can help non-specialists perform high-level screenings using Siddha parameters. The Ayush Grid project will facilitate personalized teleconsultations and digital health records, making Siddha more accessible to rural populations.

- Global Integration:

Following the Gujarat Declaration, India is leading the global effort to integrate traditional medicine into primary healthcare systems. Establishing Ayush chairs and collaborations across 42 countries is a step toward this goal.

- Modernizing Diagnostics:

The shift from manual to sensor-based diagnostics, as seen in digital Naadi and IoT-based Manikadai Nool, will improve the accuracy and credibility of Siddha pathology.

- Standardizing Manufacturing:

Moving from fragmented, small-scale production to enterprise-level, GMP-certified manufacturing will enable Indian Siddha products to meet the compliance expectations of developed markets, particularly in stress management and metabolic health.

VI. CONCLUSION

The Siddha system of medicine offers an exhaustive and insightful approach to pathology through its unique diagnostic parameters. By integrating Envagai Thervu, Manikadai Nool, and Maruthuva Jothidam into public health frameworks, healthcare systems can move toward a more holistic, person-centered model. While significant policy gaps and professional resistance remain, the commitment to medical pluralism and the advancement of digital health tools suggest a promising future. Strengthening scientific validation and standardization will be the key to ensuring that Siddha remains not just a heritage-driven system but a vital, modern healthcare asset.

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Impact of Social Media on Education in Primary Schools Perceptions of Teachers and Parents in Urban Primary Schools in Suva, Fiji

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***Abstract*—The use of social media has rapidly increased in education, influencing teaching and learning practices in primary schools. This study explores the impact of social media on education through the perceptions of teachers and parents in urban primary schools in Suva, Fiji. Social media platforms such as Facebook, WhatsApp, YouTube, and TikTok are increasingly being used for communication, collaboration, and learning support. However, concerns remain regarding distraction, cyberbullying, reduced academic focus, and exposure to inappropriate content. This study adopts a qualitative research approach using interviews and questionnaires to collect data from teachers and parents. Findings reveal that social media has both positive and negative impacts on students' educational development. Positively, it enhances communication, access to learning materials, and student engagement. Negatively, excessive use affects concentration, discipline, and academic performance. The study recommends balanced usage, parental monitoring, teacher guidance, and digital literacy programs in schools.**

***Index Terms*—Social Media, Education, Primary Schools, Teachers' Perceptions, Parents' Perceptions, Fiji**

I. INTRODUCTION

Background of the Study

Social media has become an important part of modern society, especially among young learners. In primary schools, children are exposed to digital platforms at an early age. These platforms influence how they communicate, access information, and interact with educational content.

In Fiji, the widespread use of smartphones and internet connectivity has made social media more accessible. During the COVID-19 pandemic, schools relied heavily on digital communication tools, making social media a vital educational support system. Parents and teachers began using WhatsApp and Facebook groups for sharing lessons, assignments, and important notices.

Despite these benefits, there are challenges such as addiction, cyberbullying, and distractions that can negatively impact students' learning.

Problem Statement

Although social media has become widely integrated into educational settings, there is limited research in Fiji focusing on how teachers and parents perceive its influence on primary school education. Understanding these perceptions is important to guide effective educational practices.

Research Objectives

1. To explore teachers' perceptions of social media in primary education.
2. To examine parents' views on social media's influence on children's learning.
3. To identify the positive and negative impacts of social media on students' academic performance.
4. To recommend strategies for effective social media use in education.

Research Questions

1. What are teachers' perceptions of social media in education?
2. What are parents' perceptions of social media's role in learning?
3. What benefits and challenges does social media bring to primary school education?
4. How can social media be used effectively to support learning?

Significance of the Study

This study contributes to educational knowledge by highlighting how social media affects learning in primary schools. It will help teachers, parents, school leaders, and policymakers understand how to manage and integrate social media responsibly.

II. LITERATURE REVIEW

Concept of Social Media in Education

Social media refers to online platforms that allow users to create and share content. In education, it supports communication, collaboration, and access to information.

According to □entity□["company", "Facebook", "Meta Platforms social media platform"]□, □entity□["company", "WhatsApp", "Meta messaging platform"]□, and □entity□["company", "YouTube", "Google video-sharing platform"]□, educational materials can be shared instantly.

Positive Impacts of Social Media

- Enhances communication between teachers and parents.
- Provides quick access to educational resources.
- Encourages collaborative learning.
- Improves digital literacy skills.

- Supports remote learning.

Studies show that students can learn through educational videos and online discussions.

Negative Impacts of Social Media

- Causes distractions during study.
- Reduces concentration and reading habits.
- Exposure to harmful content.
- Cyberbullying and online harassment.
- Addiction and excessive screen time.

Parents often express concern about children spending too much time on social media rather than studying.

Theoretical Framework

This study is guided by Social Learning Theory by □entity□[“people”,“Albert Bandura”,“Canadian-American psychologist”]□. The theory explains that children learn by observing others. Social media exposes children to various behaviours and knowledge that influence learning.

III. METHODOLOGY

Research Design

This study uses a qualitative research design to explore perceptions and experiences.

Research Site

The study will be conducted in selected urban primary schools in Suva, Fiji.

Participants

Participants will include:

- 10 teachers
- 15 parents

Purposive sampling will be used.

Data Collection Methods

Interviews

Semi-structured interviews will be conducted with teachers.

Questionnaires

Open-ended questionnaires will be given to parents.

Data Analysis

Thematic analysis will be used to identify patterns and themes from the data.

Ethical Considerations

- Consent will be obtained from all participants.
- Confidentiality will be maintained.
- Participation will be voluntary.
- Ethical approval will be sought from the relevant educational authority.

IV. FINDINGS AND DISCUSSION

Theme 1: Improved Communication
Teachers reported that WhatsApp groups made communication easier with parents.
Teacher Response: “It helps us send homework and reminders quickly.”
Parents agreed that they receive updates instantly.

Theme 2: Access to Learning Resources
Parents highlighted that YouTube videos help children understand difficult topics.

Theme 3: Distraction and Misuse
Most teachers mentioned students being distracted by entertainment apps like TikTok.
Parent Response: “My child spends too much time watching videos instead of studying.”

Theme 4: Need for Monitoring
Both teachers and parents stressed the importance of monitoring children’s social media use.

V. CONCLUSION AND RECOMMENDATIONS

Conclusion
The study found that social media has both positive and negative effects on primary school education. While it supports communication and access to resources, it can also create distractions and reduce academic focus.

Recommendations

1. Schools should develop social media usage policies.
2. Parents should monitor children’s online activities.
3. Teachers should guide students on educational use of social media.
4. Digital literacy programs should be introduced.
5. Awareness programs on cyber safety should be conducted.

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Bifurcation Deferred a Case Comment on Klesch Group Holdings Limited and Others v European Union, Denmark and Germany

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I. INTRODUCTION

Since October 2023 the Klesch Group has been pursuing three parallel investment treaty claims against the European Union, the Kingdom of Denmark and the Federal Republic of Germany under the Energy Charter Treaty ('ECT'), arising out of the 'solidarity contribution' — an emergency windfall levy on fossil fuel companies introduced across the Union in response to the 2022 energy crisis.[1] Framed by its critics as an unprecedented attempt to relitigate a democratically enacted tax through investor-State dispute settlement, and by the Claimants as a straightforward application of ECT protections to a confiscatory measure, the Klesch arbitrations have already produced a rich and closely-watched procedural record. The first substantive ruling — the Tribunal's Decision on the Respondents' Request for Bifurcation, issued on 8 April 2025 — dismissed, by majority, an application to have four separate preliminary objections decided before the merits. This comment examines the factual and regulatory background to the dispute, the four objections raised, the Tribunal's reasoning for declining to bifurcate them, and the broader significance of the decision for the treatment of the recurring 'intra-EU objection' and for ECT-based challenges to European energy windfall taxes more generally.

II. FACTUAL AND REGULATORY BACKGROUND

The dispute originates in Council Regulation (EU) 2022/1854, adopted on 6 October 2022, which introduced an emergency 'solidarity contribution' on the surplus profits of undertakings active in the crude petroleum, natural gas, coal and refinery sectors, in order to fund household and business

[1]Decision on Respondents' Request for Bifurcation, Klesch Group Holdings Limited & Others v. European Union (ICSID Case No. ARB(AF)/23/1), Klesch Group Holdings Limited & Others v. Kingdom of Denmark (ICSID Case No. ARB/23/48), and Klesch Group Holdings Limited & Another v. Federal Republic of Germany (ICSID Case No. ARB/23/49), 8 April 2025 ('Decision'), para. 3.

support during the energy crisis triggered by Russia's invasion of Ukraine.[2] Denmark implemented the Regulation through Act No. 502 of 16 May 2023, and Germany through Article 40 of its Annual Tax Act 2022.[3] The Claimants are entities within the Klesch Group: Klesch Group Holdings Limited, a Jersey-incorporated holding company, together with its Danish subsidiaries Klesch Refining Denmark A/S and Kalundborg Refinery A/S (which operate the Kalundborg refinery in Denmark), and its German subsidiary Raffinerie Heide GmbH (which operates the Heide refinery in Schleswig-Holstein).[4] The Claimants' home States for treaty purposes are identified as Germany, Denmark and the United Kingdom[5] — the latter connection being made through the Jersey holding vehicle, a structure that has attracted comment given that Jersey is a UK Crown Dependency and the ECT remained applicable to the United Kingdom notwithstanding Brexit.

The Klesch Group's German asset had itself previously been a beneficiary of European public support, including a reported EUR 30 million contribution toward a hydrogen facility at the Heide refinery in 2020, against a background in which the Group's principal, Gary Klesch, had publicly criticised EU investment regulation as burdensome.[6] The Claimants now allege that the solidarity contribution exposes them to current and future payment obligations aggregating approximately EUR 175.5 million, and that its imposition and enforcement breach Articles 10(1), 10(3), 10(7) and 13 of the ECT — respectively, the fair and equitable treatment, most-favoured-nation, 'umbrella clause' and expropriation protections.[7]

III. PROCEDURAL HISTORY

The Claimants commenced three separate ICSID proceedings in October 2023: an Additional Facility arbitration against the European Union (ICSID Case No. ARB(AF)/23/1, the Union not being a Contracting State to the ICSID Convention), and two ICSID Convention arbitrations against Denmark (ARB/23/48) and Germany (ARB/23/49).[8] A single tribunal — Mr Cavinder Bull SC (President), Judge O. Thomas Johnson Jr and Professor Jorge E. Viñuales — was constituted

[2]Council Regulation (EU) 2022/1854 of 6 October 2022 on an emergency intervention to address high energy prices, OJ L 261I, 7.10.2022.

[3]Decision, para. 3, referring to Danish Act No. 502 of 16 May 2023 and Article 40 of the German Annual Tax Act 2022.

[4]Decision, para. 2.

[5]UNCTAD Investment Policy Hub, Investment Dispute Settlement Navigator, 'Klesch v. EU', ICSID Case No. ARB(AF)/23/1, listing the home States of the investors as Germany, Denmark and the United Kingdom.

[6]Global Arbitration Review (n 6), reporting that the German government contributed EUR 30 million toward a hydrogen facility at the Heide refinery in 2020, and recalling earlier public comments by Gary Klesch criticising EU investment regulation.

[7]Decision, para. 3.

[8]Decision, paras. 1-2.

across all three cases, which the parties agreed to coordinate procedurally to the extent possible.[9] On 9 December 2024 the three respondents filed a joint Request for Bifurcation seeking the preliminary determination of four objections; the Claimants answered on 23 January 2025, and a joint hearing was held in Paris on 19 March 2025, closed to the public.[10] Given the substantial overlap between the submissions in the Three Arbitrations, the Tribunal issued a single Decision addressing the Request across all three cases.[11]

The proceedings also unfold against the backdrop of the European Union's withdrawal from the ECT, which took effect on 27 June 2024. Because Article 47(3) of the ECT contains a twenty-year 'sunset clause' preserving treaty protection for investments made before a Contracting Party's withdrawal takes effect, the Union's exit — and the parallel exits of Denmark, Germany and other Member States — does not extinguish jurisdiction over pre-existing claims such as those brought by Klesch.[12] The case is accordingly a live illustration of the practical durability of ECT protection notwithstanding coordinated withdrawal by EU Member States.

IV. THE FOUR PRELIMINARY OBJECTIONS

The Respondents advanced four objections, three of which (Objections A, C and D) were raised by all three respondents, while Objection B was raised only by Denmark and Germany.

A. Objection A — the 'intra-EU' objection

Objection A contends that the Tribunal lacks jurisdiction because neither the Union nor its Member States gave, or could give, valid consent under Article 26(3)(a) of the ECT to arbitrate disputes between investors connected to EU Member States and the Union or a Member State.[13] The Respondents relied principally on the Court of Justice of the European Union's decisions in Achmea and Komstroy, together with EU law more generally, for the proposition that Article 26 ECT does not apply to intra-EU disputes, with the consequence that no valid offer to arbitrate was ever made.[14] A further, case-specific wrinkle was added: because the Claimants' asserted UK nationality is routed through a Jersey holding company incorporated while the United Kingdom was still an EU Member State, the Respondents argued that no valid consent existed even at the outset, and that the UK made no fresh offer to arbitrate following its withdrawal from the Union.[15]

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[9]Decision, para. 5(a).
[10]Decision, paras. 5(b)-5(c).
[11]Decision, para. 6.
[12]Energy Charter Treaty (1994), Art. 47(3) (sunset clause); IBFD, 'Legality of the solidarity contribution under international law' (2025), noting the EU's withdrawal from the ECT took effect on 27 June 2024.
[13]Decision, paras. 11-12; Energy Charter Treaty, Art. 26(3)(a).
[14]Decision, para. 12, referring to Case C-284/16, Slowakische Republik v Achmea BV, Judgment of 6 March 2018, and Case C-741/19, République de Moldavie v Komstroy, Judgment of 2 September 2021.
[15]Decision, para. 12.

B. Objection B — the proper respondent

Objection B, raised only by Denmark and Germany, contends that those States never gave consent to arbitrate under Article 26(3) ECT because, pursuant to Article 1(3) of the ECT (which addresses the position of Regional Economic Integration Organisations such as the Union) and the mechanism set out in the Statement submitted to the ECT Secretariat in 2019, responsibility for measures implementing EU law is to be allocated ex post between the Union and its Member States in accordance with Regulation (EU) No 912/2014.[16] Denmark and Germany asserted that, applying that mechanism, the European Commission notified the Claimants on 14 November 2023 that the Union — not Denmark or Germany — would be the sole respondent and would bear full financial liability, and that the Claimants were bound to accept that determination.[17][18]

C. Objection C — the taxation carve-out

Objection C invokes Article 21 of the ECT, which excludes 'Taxation Measures' from the scope of most substantive protections, including Article 10. The Respondents characterised the solidarity contribution as a direct tax on corporate net income falling within Article 21(7), with the consequence that the Tribunal would lack jurisdiction over the Claimants' Article 10 claims, leaving only the Article 13 expropriation claim (which is carved back into the taxation exception under Article 21(5)) available for adjudication.[19]

D. Objection D — the essential security exception

Objection D relies on Article 24(3)(a)(ii) of the ECT, which permits a Contracting Party to take measures it considers necessary for the protection of its essential security interests in an emergency in international relations, without those measures being reviewable under most of the Treaty's protections. The Respondents argued that the solidarity contribution was adopted specifically to address the effects of Russia's invasion of Ukraine on European energy security, and therefore fell within the exception, again leaving only the expropriation claim outstanding.[20]

V. THE APPLICABLE STANDARD ON BIFURCATION

There is no presumption for or against bifurcation in ICSID proceedings.[21] Rule 54(2) of the ICSID Additional Facility Arbitration Rules 2022 and the identically worded Rule 44(2) of the ICSID Arbitration Rules 2022 direct a tribunal to consider 'all relevant circumstances', including whether

[16]Decision, para. 13; Energy Charter Treaty, Art. 1(3) (definition of a Regional Economic Integration Organisation).
[17]Decision, paras. 14-15, referring to the Statement submitted to the ECT Secretariat pursuant to Article 26(3)(b)(ii) of the ECT, published 2 May 2019, and Regulation (EU) No 912/2014.
[18]Decision, para. 15.
[19]Decision, paras. 16-17; Energy Charter Treaty, Art. 21(1) and 21(7) (Taxation Measures).
[20]Decision, paras. 18-20; Energy Charter Treaty, Art. 24(3)(a)(ii).
[21]ICSID Additional Facility Arbitration Rules 2022, r. 54(2); ICSID Arbitration Rules 2022, r. 44(2).

bifurcation would materially reduce the time and cost of the proceeding, whether determination of the preliminary objection would dispose of all or a substantial portion of the dispute, and whether the objection is so intertwined with the merits as to make bifurcation impractical.[22] The Tribunal accepted the parties' shared position that this inquiry is also informed by a threshold requirement that the objections be prima facie serious and substantial, and by an overarching question of procedural fairness and efficiency.[23]

VI. THE TRIBUNAL'S REASONING

By majority (President Bull and Judge Johnson; Professor Viñuales dissenting throughout), the Tribunal dismissed the Request for Bifurcation in its entirety.

1. Objection B

The majority's central reasoning on Objection B was that excising Denmark and Germany as named respondents would not meaningfully shrink the dispute, because the conduct of those two States would remain squarely at issue in the EU Arbitration regardless of the outcome.[24] At the hearing, the Respondents themselves confirmed that, even if Objection B succeeded, the Tribunal would still be required to assess Denmark's and Germany's conduct against the ECT and, if a breach were found, simply enter an award against the Union.[25] The majority also considered that Objection B raises a genuinely novel question — how responsibility is allocated between the Union and its Member States for measures implementing EU secondary legislation — on which no ICSID tribunal had previously ruled, and which was better resolved with the benefit of a full evidentiary record rather than in the abstract.[26] It further noted uncertainty as to precisely which competences Denmark and Germany claim to have transferred to the Union for these purposes, and observed that Regulation (EU) No 912/2014 appears on its face to allocate financial responsibility rather than to speak to consent to arbitrate at all.[27] Professor Viñuales dissented, considering that the potential termination of two of the three arbitrations in their entirety self-evidently satisfied the efficiency criteria for bifurcation.[28]

2. Objection A

On the intra-EU objection, the majority declined to speculate about its prospects of success, observing that there were at least three possible outcomes — all three arbitrations disposed of, none disposed of, or (if the Claimants were correct that Komstroy does not extend to disputes in

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[23]Decision, para. 8.
[24]Decision, paras. 30-37.
[25]Decision, paras. 33-34, quoting the Respondents' confirmation at the Hearing that the Tribunal would still be required to judge the acts of Germany and Denmark against the ECT even if Objection B succeeded (Transcript, p. 117, lines 7-17).
[26]Decision, para. 38.
[27]Decision, paras. 39-40.
[28]Decision, para. 30 (Arbitrator Viñuales, dissenting).

which the Union itself is respondent) only the Denmark and Germany Arbitrations disposed of while the EU Arbitration continued.[2930] Given that uncertainty, and the close doctrinal relationship between Objections A and B — the Respondents themselves treating B as pleaded in the alternative to A — the majority considered it more coherent to determine both together, with full submissions, at the merits stage.[31] In doing so, the majority situated its decision within a broader pattern: citing the tribunal's observation in Mainstream Renewable Power v Germany that the great majority of ECT tribunals confronted with the intra-EU objection have likewise deferred it to the merits rather than resolving it as a discrete jurisdictional threshold.[32]

3. Objections C and D

The majority treated Objections C and D similarly, and for a closely related reason. Both objections, even if fully successful, would leave the Article 13 expropriation claim standing.[33] The majority was not persuaded that adjudicating the 'Taxation Measure' characterisation, or the applicability of the essential security exception, could be confined to a narrow set of facts distinct from the merits: assessing whether the solidarity contribution was arbitrary or discriminatory — central to the surviving expropriation claim — would require the Tribunal to examine much the same conduct, and largely the same evidence, that would inform the Article 10 claims the objections seek to exclude.[34] On the majority's assessment, this evidentiary overlap meant that bifurcating Objections C and D would not achieve a genuine reduction in the scope of the merits phase, notwithstanding the Respondents' argument that a substantial share of the Claimants' pleadings was devoted to the Article 10 claims. Professor Viñuales again dissented, considering that confining the merits phase to a single claim rather than several would self-evidently be more efficient and would dispose of a 'substantial portion' of the dispute within the meaning of the Rules.[353637]

4. Disposition

The Tribunal accordingly dismissed the Request for Bifurcation, directed the parties to follow the non-bifurcated procedural timetable already contemplated in Procedural Order No. 1, and reserved

[29]Decision, paras. 42-45.
[30]Decision, para. 46, distinguishing Case C-741/19, Komstroy, para. 66, on the basis that it addresses disputes between a Member State and an investor of another Member State, not disputes involving the EU itself as respondent.
[31]Decision, paras. 48-49.
[32]Decision, para. 50, citing Mainstream Renewable Power Ltd and others v Federal Republic of Germany, para. 42.
[33]Decision, paras. 51-58.
[34]Decision, paras. 53, 57-58.
[35]Decision, para. 55 (Arbitrator Viñuales, dissenting).
[36]Decision, paras. 59-63.
[37]Decision, para. 63 (Arbitrator Viñuales, dissenting).

costs.[38] It emphasised, however, that the refusal to bifurcate was without prejudice to any future ruling on the merits of the objections themselves, all four of which remain live and will be argued together with the substance of the claims.[39]

VII. COMMENTARY

A. The intra-EU objection: deferral as the default

The Decision is a further data point in what is now a well-established pattern: ECT tribunals confronted with the intra-EU objection overwhelmingly decline to resolve it as a threshold jurisdictional matter, preferring to join it to the merits.[40] There is a certain tension in that practice. The intra-EU objection is, by its own logic, an objection to the existence of consent to arbitrate in the first place — a matter classically suited to prior determination, since a tribunal without jurisdiction has, in principle, no power to proceed to the merits at all. Yet the practical reality identified by the majority is compelling on its own terms: because Objections A and B are interlinked, and because the very scope of the 'intra-EU' concept is contested as between disputes involving Member States and disputes involving the Union itself, a tribunal asked to rule on Objection A in isolation would risk doing so on an incomplete or provisional understanding of the surrounding facts. The Klesch tribunal's approach illustrates how the cumulative, three-factor bifurcation standard under the 2022 ICSID Rules — rather than any special solicitude for the merits — increasingly operates as the mechanism through which the intra-EU objection is deferred, almost as a matter of course, across the ECT docket.

B. A structural first: the Union as substitute respondent

Objection B is the more genuinely novel feature of the case. The mechanism by which the European Commission purported to designate the Union as sole respondent for measures adopted by Denmark and Germany implementing EU secondary legislation has, on the Tribunal's own account, never been tested in an ICSID proceeding.[41] The majority's scepticism about whether a regulation allocating inter-institutional financial responsibility can, without more, answer the distinct question of consent to arbitrate is a useful signal for future respondents relying on the 2019 ECT Secretariat Statement: the architecture built around Regulation (EU) No 912/2014 may prove less procedurally decisive than the Union and its Member States have assumed. At the same time, by declining to resolve the question early, the Tribunal has left Denmark and Germany fully engaged as active (if formally non-party) participants in the merits phase for at least the two years remaining before the merits hearing — a considerable cost for States that may ultimately be found never to have been proper respondents at all.

[38]Decision, para. 64.
[39]Decision, para. 65.

C. Taxation and security carve-outs: the expropriation claim as an anchor

The Tribunal's treatment of Objections C and D reflects a structural feature of ECT pleading practice that respondent States confront with some regularity: because expropriation claims typically incorporate an assessment of the reasonableness, proportionality and non-discriminatory character of the challenged measure, a 'clean' carve-out of fair-and-equitable-treatment claims rarely removes those same factual questions from the case. Where, as here, the Claimants have pleaded an expropriation claim that survives even a successful taxation or security objection, respondents seeking bifurcation face an uphill struggle to show that the preliminary phase would meaningfully narrow the evidentiary record — a difficulty that is likely to recur wherever states rely on Article 21 or Article 24 ECT to trim, rather than eliminate, an investor's claims.

D. Wider significance

Beyond its immediate procedural consequences, the Decision is a reminder of the durability of ECT exposure notwithstanding the coordinated withdrawal of the Union and its Member States from the Treaty.[42] It also illustrates the continuing salience of corporate nationality planning in ECT practice: the Claimants' invocation of a Jersey-incorporated holding company to anchor United Kingdom nationality — and thereby to avoid at least part of the intra-EU objection — has drawn criticism from civil society observers concerned about the use of offshore structures to access investor-State arbitration against Treaty Parties.[4344] Whatever the eventual outcome, the case is likely to remain one of the more closely watched ECT proceedings of the mid-2020s, both for its bearing on the future of intra-EU investment arbitration and as a test of the limits of Article 21 and Article 24 ECT as tools for defending emergency fiscal measures adopted in response to the European energy crisis.[45]

VIII. CONCLUSION

The Klesch tribunal's Decision on Bifurcation is, on its face, a modest procedural ruling: a majority declined, and one arbitrator would have granted, an application to carve out four preliminary objections for early determination. Its real significance lies in what it reveals about how ICSID tribunals are managing the accumulated complexity of the intra-EU objection, the unresolved question of the Union's status as respondent for measures implementing its own secondary legislation, and the recurring difficulty of using the ECT's taxation and security carve-outs to

[43]ISDS Red Carpet Courts (n 8), noting that all three respondents, together with the EU, have withdrawn or are withdrawing from the ECT, and observing the effect of the Treaty's twenty-year sunset clause under Article 47(3).

[44]ISDS Red Carpet Courts (n 8).

[45]See generally Kyla Tienhaara and Lorenzo Cotula, 'Raising the Cost of Climate Action? Investor-State Dispute Settlement and Compensation for Stranded Fossil Fuel Assets' (IIED/Queen's University, 2020), on the recurrent use of ECT arbitration to challenge State climate and energy measures.

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narrow claims that are anchored by a surviving expropriation cause of action. By declining to bifurcate, the Tribunal has committed the parties — and itself — to a long, factually dense merits phase, expected to conclude only in 2027, in which all four objections, and the underlying claims they target, will be argued together. The eventual outcome will be an important precedent both for the closing chapter of intra-EU ECT arbitration and for the broader question of how far investment treaties can be used to contest emergency energy taxation adopted across the European Union.

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Factors Contributing to Umbilical Cord Infection among Neonates Admitted to the Neonatal Intensive Care Unit at Kagando Hospital, Kasese District

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***Abstract*—Introduction: Umbilical cord infection, also referred to as omphalitis or umbilical cord sepsis, is an important neonatal health problem because the newly cut umbilical cord can provide a pathway for bacterial invasion and may contribute to neonatal morbidity and mortality. This study assessed factors contributing to umbilical cord infection among neonates admitted to the Neonatal Intensive Care Unit (NICU) at Kagando Hospital, Kasese District.**

Purpose: The study determined factors contributing to umbilical cord infection among neonates admitted to the NICU at Kagando Hospital, Kasese District.

Methods: A cross-sectional quantitative study design was used. Data were collected from 32 caretakers using an interviewer-administered semi-structured questionnaire. Respondents were selected using purposive sampling. Data were coded, tallied and summarized using frequencies and percentages, and findings were presented in tables and figures.

Results: Among the 32 respondents, 14 (43.8%) reported applying Vaseline to the baby's cord, 8 (25.0%) reported applying saliva, 4 (12.5%) reported applying breast milk and 3 (9.4%) reported applying cow dung. Eighteen (56.3%) respondents reported attending antenatal care fewer than four times. Sixteen (50.0%) reported greenish amniotic fluid and 12 (37.5%) reported becoming sick during delivery. Sixteen (50.0%) reported that their babies did not cry immediately after birth, while 2 (6.3%) reported breech presentation and 8 (25.0%) reported that their babies were born sick. All 32 (100.0%) respondents reported that health workers did not educate them on cord care. Twenty (62.5%) reported that health workers sometimes washed their hands before touching the cord, while 30 (93.8%) reported that only one to two health workers were available on the ward per shift.

Conclusion: The reported findings indicate that maternal, neonatal and health-facility factors may contribute to umbilical cord infection among neonates admitted to the NICU at Kagando Hospital. Important concerns included potentially inappropriate substances applied to the cord, inadequate antenatal care attendance, adverse intrapartum conditions,

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low immediate newborn responsiveness, inconsistent hand hygiene, lack of maternal education on cord care and inadequate staffing.
Recommendation: The Ministry of Health and relevant health managers should strengthen comprehensive cord-care education during antenatal, intrapartum and postnatal care, address harmful myths and practices, strengthen community health education, reinforce hand hygiene and infection-prevention practices, and consider staffing needs within neonatal care services.

***Index Terms*—Umbilical Cord Infection, Omphalitis, Neonatal Sepsis, Cord Care, Neonates, Neonatal Intensive Care Unit, Kagando Hospital**

Operational Definitions

Term	Operational Definition
Apgar Score	A clinical tool used by healthcare providers to assess a newborn's condition immediately after birth.
Breech Presentation	A fetal presentation in which the fetus is in a longitudinal lie and the podalic pole presents at the pelvic brim.
Primigravida	A woman who is pregnant for the first time.
Umbilical Cord Infection	Pus discharge with erythema of the abdominal skin and umbilical cord, or severe redness extending more than 2 cm from the umbilical cord stump, with or without pus.

I. INTRODUCTION

Umbilical cord infection, also known as omphalitis, is characterized by pus discharge with erythema of the abdominal skin and umbilical cord, or severe redness extending more than 2 cm from the umbilical cord stump, with or without pus [1, 2]. The newly cut umbilical cord can provide a pathway for bacterial infection and may contribute to newborn sepsis and death [3].
Globally, neonatal umbilical cord infection remains an important health problem, particularly in settings where births occur without skilled attendants and where potentially unsafe cord-care practices are common [4, 5]. The unhealed umbilical cord may serve as an entry point for local and invasive infection and can be rapidly colonized by bacteria from the environment [6].
In low-resource settings, umbilical cord infection remains an important contributor to neonatal illness and death. Studies have reported substantial variation in prevalence across settings, including Nepal and Egypt, while neonatal deaths associated with infection continue to place a major burden on health systems in low-income countries [7, 8].

Sub-Saharan Africa carries a substantial burden of neonatal morbidity and mortality associated with infection, with higher risks reported in communities where non-sterile substances are applied to the umbilical cord [1]. In Pemba Island, Zanzibar and Tanzania, omphalitis was reported among 954 (5.5%) of 17,198 infants within seven days of age [9]. Other assessments have documented varying degrees of umbilical cord redness, pus and foul odour among newborns [10].

In Uganda, neonatal infection remains an important public health concern. Ministry of Health reports have highlighted newborn infection among causes of neonatal morbidity and mortality and emphasized the importance of infection prevention and quality newborn care [11].

At Kagando Hospital, records from July 2025 to December 2025 showed that 186 neonates were admitted to the NICU. Ninety-seven (52.2%) were delivered at Kagando Hospital and, among those born at the hospital, 53 (54.6%) had neonatal sepsis reported as secondary to umbilical cord infection. Of these, 4 (7.5%) died, 5 (9.4%) developed seizures and 18 (34.0%) had a hospital stay of more than two weeks. These observations motivated the study of factors contributing to umbilical cord infection among neonates admitted to the NICU at Kagando Hospital.

1.1 Problem Statement

Despite improvements in labour-suite practices, instrument sterilization, surgical techniques, use of antiseptic solutions such as chlorhexidine, and infection-prevention strategies, umbilical cord infection remains a concern for newborns and health systems because of its potential to cause morbidity, prolonged hospital stay and increased healthcare costs. At Kagando Hospital, NICU records for July to December 2025 indicated a substantial burden of neonatal sepsis among neonates born at the hospital. The reported cases included deaths, seizures and prolonged hospital admissions. However, maternal, neonatal and health-facility factors contributing to umbilical cord infection in this setting had not been systematically documented. Therefore, this study was conducted to identify factors contributing to umbilical cord infection among neonates admitted to the NICU at Kagando Hospital, Kasese District.

1.2 Purpose of the Study

The purpose of the study was to determine factors contributing to umbilical cord infection among neonates admitted to the NICU at Kagando Hospital, Kasese District.

1.3 Specific Objectives

To determine maternal-related factors contributing to umbilical cord infection among neonates admitted to the NICU at Kagando Hospital.

To determine neonatal-related factors contributing to umbilical cord infection among neonates admitted to the NICU at Kagando Hospital.

To determine health-facility-related factors contributing to umbilical cord infection among neonates admitted to the NICU at Kagando Hospital.

1.4 Research Questions

1. What maternal-related factors contribute to umbilical cord infection among neonates admitted to the NICU at Kagando Hospital?

2. What neonatal-related factors contribute to umbilical cord infection among neonates admitted to the NICU at Kagando Hospital?
3. What health-facility-related factors contribute to umbilical cord infection among neonates admitted to the NICU at Kagando Hospital?

1.5 Justification of the Study

Hygienic umbilical cord care is important in preventing neonatal umbilical cord infection. Although chlorhexidine is recommended in settings where potentially harmful traditional cord-care practices are common, evidence indicates that substances such as cow dung, oil, saliva and other non-recommended products may still be applied to the umbilical cord. Such practices can expose newborns to infection. Therefore, identifying maternal, neonatal and health-facility factors contributing to umbilical cord infection at Kagando Hospital can provide information to guide prevention and improve neonatal outcomes.

1.6 Significance of the Study

The findings may be useful to healthcare providers, hospital managers, policymakers, educators and researchers by highlighting modifiable factors associated with cord care and infection prevention.

1.6.1 Nursing Practice

The findings may help nurses and midwives strengthen aseptic techniques, maternal counselling, early recognition of cord infection and newborn infection-prevention practices.

1.6.2 Nursing Research

The findings may contribute to the body of knowledge on umbilical cord care and provide a basis for further research in similar settings.

1.6.3 Nursing Management and Administration

The information may assist hospital management in planning continuing medical education and strengthening infection-prevention and maternal education activities.

1.6.4 Nursing Education

The information may be useful to tutors and students when teaching neonatal care, infection prevention and umbilical cord care.

II. LITERATURE REVIEW

The literature reviewed maternal, neonatal and health-facility factors that may contribute to umbilical cord infection among neonates. Evidence was drawn from books, journal articles and electronic sources.

2.1 Maternal-Related Factors

2.1.1 Home Delivery

In studies of community-based omphalitis, home delivery, unhygienic cord cutting, application of unclean substances and covering the stump with unclean fabric were identified as potential contributors to neonatal infection [9].

2.1.2 Cultural Norms and Practices

Studies have documented cultural practices involving the umbilical cord, including rituals and application of substances. Such practices may influence how mothers and caregivers manage the cord after birth [12].

2.1.3 Herbal Medication Use

Studies in Uganda and other low- and middle-income countries have reported the use of herbal mixtures and other substances for cord care. Reported substances include petroleum jelly, herbs, saliva, onion, charcoal powder and ash [3, 13].

2.1.4 Maternal Knowledge

Knowledge may influence cord-care practices. Kyomugisha (2022) reported generally sufficient knowledge among mothers in one Ugandan setting, whereas Asiedu et al. (2023) reported insufficient knowledge among a proportion of mothers and caregivers in Ghana [14, 15].

2.1.5 Economic Status

Socioeconomic status can influence access to health services and the type of newborn-care practices used. Uwingabire et al. (2020) reported substantial financial constraints among postnatal mothers in Rwanda, while Eyeberu et al. (2022) linked socioeconomic circumstances with newborn-care practices [16, 17].

2.1.6 Antenatal Care

Attendance at antenatal care provides opportunities for maternal education, including counselling on newborn and cord care. Merga et al. (2022) reported that antenatal care attendance was relevant to exposure to information on cord care [18].

2.1.7 Place of Delivery

Health-facility delivery may provide greater opportunities for skilled birth attendance and appropriate cord care. Sivalogan et al. (2023) reported better cord-care practices among facility deliveries, while Gelana-Fedaku et al. (2022) found higher odds of potentially harmful traditional cord care among mothers who delivered at home [19, 20].

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2.1.8 Level of Education

Educational attainment may influence the ability to understand health information and seek appropriate care. Teferi et al. (2024) reported poorer cord-care practices among women with lower educational attainment compared with those with tertiary education [21].

2.1.9 Source of Information

Information from health workers may support safer cord-care practices, whereas information from relatives and friends may reinforce traditional practices. Amare (2023) and Mukunya et al. (2020) highlighted the influence of family and community knowledge on cord care [22, 23].

2.1.10 Premature Rupture of Membranes

Premature rupture of membranes may increase exposure of the fetus and newborn to infection. De-Jonge et al. (2022) reported an association between premature rupture of membranes and neonatal infection [24].

2.1.11 Type of Amniotic Fluid

Abnormal or foul-smelling amniotic fluid may indicate infection and has been associated with increased risk of neonatal infection in some studies [25].

2.1.12 Maternal Intrapartum Infections

Maternal infection during labour may expose the newborn to pathogens before or during birth. Dessalegn et al. (2022) reported an association between maternal intrapartum infection and neonatal cord sepsis [26].

2.2 Neonatal-Related Factors

2.2.1 Apgar Score

Low Apgar scores have been associated with neonatal morbidity and sepsis in several studies. A low score may reflect physiological compromise and the need for resuscitation or increased clinical care [27, 28, 29].

2.2.2 Breech Presentation

Breech presentation is associated with increased risks of birth complications and neonatal morbidity. Roble et al. (2022) reported breech presentation among factors considered in relation to neonatal umbilical cord sepsis [30].

2.2.3 Infection at Birth

Neonatal infection may occur in association with maternal and intrapartum risk factors, including premature rupture of membranes. Exposure to pathogens before or during delivery can increase vulnerability of the newborn [31].

2.3 Health-Facility-Related Factors

2.3.1 Education of Mothers

Health workers can influence maternal knowledge and practices through education during antenatal, delivery and postnatal care. Community health-worker interventions have demonstrated the potential to improve maternal and newborn-care practices [32, 19, 16].

2.3.2 Performing Invasive Procedures

Invasive procedures may increase opportunities for pathogen transmission if infection-prevention measures are not consistently followed. Olaniran et al. (2019) emphasized the importance of adequate infection prevention in maternal and newborn services [33].

2.3.3 Hand Washing

Hand hygiene is a basic infection-prevention measure. Inadequate hand hygiene can facilitate transfer of microorganisms to newborns and their umbilical cords [34].

2.3.4 Vaginal Examination

Frequent vaginal examinations during labour may increase exposure to pathogens, particularly where infection-prevention practices are inadequate. Rajabi (2025) reported increased risk associated with multiple examinations [35].

2.3.5 Inadequate Staffing

Insufficient human resources may reduce the amount of time available for individual newborn care and infection-prevention activities. Stella et al. (2021) highlighted the potential effects of unequal distribution of health workers on quality of care [36].

III. METHODS

3.1 Study Design and Rationale

A cross-sectional quantitative study design was used. The design was appropriate because information on maternal, neonatal and health-facility factors was collected during a defined study period. Data were collected using a semi-structured interviewer-administered questionnaire. The design was considered suitable for the available time and resources.

3.2 Study Setting and Rationale

The study was conducted at Kagando Hospital in Kasese District, Uganda. The hospital is located approximately 470 km from Kampala and about 46 km from Kasese municipality. It is situated in Bukonzo East Constituency, Kisinga Town Council. The area includes lowland and mountainous terrain and is predominantly inhabited by Bakonzo, with other communities including Basongora and Banyabindi. The major economic activity is farming. The setting was selected because it was accessible to the researcher and had the target respondents required to address the study objectives.

3.3 Study Population

The study population comprised caretakers attending to neonates admitted to the NICU at Kagando Hospital. Caretakers were selected because they were directly involved in the care of the neonates and could provide information relevant to the study.

3.4 Sample Size Determination

The study used the Krejcie and Morgan (1970) sample-size table. The reported target population was 35 neonates, for which the table gives a sample size of 32. Therefore, 32 respondents were included in the study.

3.5 Sampling Procedure

Purposive sampling, a non-probability sampling technique, was used to select respondents who met the eligibility criteria and were available during the study period.

3.6 Inclusion and Exclusion Criteria

3.6.1 Inclusion Criteria

Caretakers of neonates admitted to the NICU who consented to participate were eligible for inclusion.

3.6.2 Exclusion Criteria

Caretakers who did not consent to participate were excluded from the study.

3.7 Definition of Variables

3.7.1 Dependent Variable

The dependent variable was neonatal umbilical cord infection.

3.7.2 Independent Variables

- Maternal-related factors: age, education level, place of delivery, antenatal care attendance, source of information, substances applied to the cord, membrane rupture, amniotic fluid characteristics and maternal illness during delivery.
- Neonatal-related factors: Apgar-related newborn condition, crying at birth, breech presentation and illness at birth.
- Health-facility-related factors: staffing, maternal education, invasive procedures, hand hygiene, cord-tying materials and vaginal examinations.

3.8 Research Instrument

A closed-ended semi-structured interviewer-administered questionnaire was used. It contained sections on demographic characteristics, maternal-related factors, neonatal-related factors and health-facility-related factors contributing to umbilical cord infection.

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3.9 Data Collection Procedure

Data collection was conducted over one month, with approximately eight mothers engaged per week.

3.10 Data Management

3.10.1 Coding

Responses were grouped into categories and coding frames were developed to facilitate organization and analysis of the data.

3.10.2 Data Entry

Data were entered using tally marks and double-entry procedures on separate sheets to reduce entry errors.

3.10.3 Editing

Completed questionnaires were checked for completeness, consistency, validity, relevance and accuracy immediately after data collection.

3.10.4 Data Analysis

Data were analyzed manually using tallying, frequency counts and percentages. Findings were summarized and presented using frequency tables and figures. The analysis was descriptive and did not include inferential statistical testing.

3.11 Quality Control

1. The questionnaire was developed from the available literature and pretested at Bwera Hospital using 10% of the sample size before use at Kagando Hospital.
2. A research assistant was trained to assist with administration of the interviews.
3. Completed questionnaires were checked for consistency and completeness.
4. All questionnaires were double-checked before closure and storage.

3.12 Ethical Considerations

Authorization was obtained through an introductory letter from the principal tutor of Bwera School of Nursing and Midwifery through the chairperson of the Institutional Research Committee. The letter was presented to the Principal Nursing Officer at Kagando Hospital, who granted permission to collect data. Participants were informed about the study and only those who consented participated. Names and personal identifiers were not recorded, and information collected was treated confidentially. All stakeholders were treated with honesty, fairness and respect.

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3.13 Dissemination of Results

The final research report was prepared and copies were intended for the Uganda Health Professions Assessment Board, Bwera School of Nursing and Midwifery library, Kagando Hospital and the research supervisor.

IV. RESULTS

4.1 Demographic Characteristics

Variable	Category	Frequency	Percentage
Age	20–30 years	12	37.5
	31–40 years	15	46.9
	41–50 years	5	15.6
Religion	Catholic	15	46.9
	Anglican	12	37.5
	SDA	3	9.4
	Full Gospel	2	6.3
Occupation	Peasant	13	40.6
	Civil servant	2	6.3
	Self-employed	10	31.3
	None	7	21.9
Education	Primary	16	50.0
	Secondary	4	12.5
	Tertiary	4	12.5
	Never went to school	8	25.0

Most respondents (15, 46.9%) were aged 31–40 years, followed by 12 (37.5%) aged 20–30 years and 5 (15.6%) aged 41–50 years. Catholics constituted 15 (46.9%) respondents, Anglicans 12 (37.5%), SDA 3 (9.4%) and Full Gospel 2 (6.3%). Thirteen (40.6%) respondents were peasants, 10 (31.3%) were self-employed, 7 (21.9%) had no occupation and 2 (6.3%) were civil servants. Sixteen (50.0%) had primary education, 8 (25.0%) had never attended school, 4 (12.5%) had secondary education and 4 (12.5%) had tertiary education.

4.2 Maternal-Related Factors

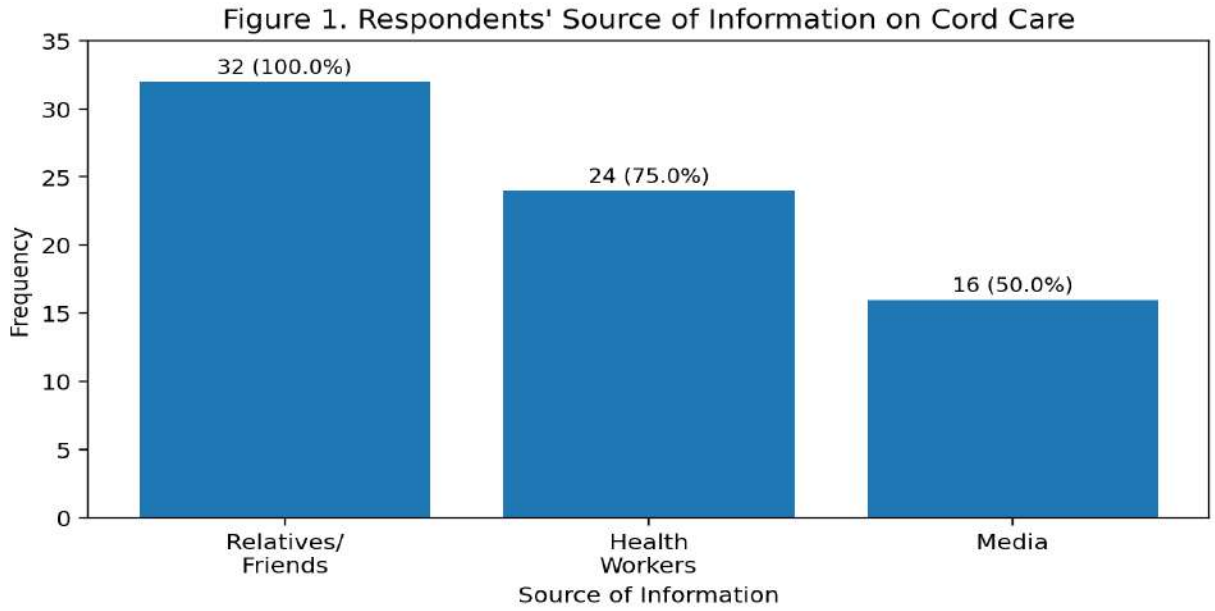
Variable	Category	Frequency	Percentage
Place of delivery	Health facility	18	56.3
	Home	12	37.5
	On the way to health facility	2	6.3
Substance applied to cord	Cow dung	3	9.4

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Variable	Category	Frequency	Percentage
	Vaseline	14	43.8
	Saliva	8	25.0
	Breast milk	4	12.5
	None	3	9.4
ANC attendance	Less than 4 times	18	56.3
	4 times	8	25.0
	5 times and above	6	18.8

Most respondents (18, 56.3%) reported a health-facility delivery, 12 (37.5%) reported home delivery and 2 (6.3%) delivered on the way to a health facility. Fourteen (43.8%) reported applying Vaseline to the cord, 8 (25.0%) saliva, 4 (12.5%) breast milk and 3 (9.4%) cow dung, while 3 (9.4%) reported applying nothing. Eighteen (56.3%) respondents attended antenatal care fewer than four times, 8 (25.0%) attended four times and 6 (18.8%) attended five or more times.

Figure 1. Respondents' Source of Information on Cord Care



All 32 (100.0%) respondents reported receiving information on cord care from relatives and friends; 24 (75.0%) reported health workers as a source and 16 (50.0%) reported media as a source. Multiple responses were possible.

Variable	Category	Frequency	Percentage
Time of membrane rupture	Before start of labour	8	25.0
	Early but during labour	8	25.0
	At delivery	16	50.0

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Variable	Category	Frequency	Percentage
Colour of amniotic fluid	Clear	10	31.3
	Greenish	16	50.0
	Not sure	6	18.8
Became sick during delivery	No	20	62.5
	Yes	12	37.5

Sixteen (50.0%) respondents reported that membranes ruptured at delivery, 8 (25.0%) before the start of labour and 8 (25.0%) early during labour. Sixteen (50.0%) reported greenish amniotic fluid, 10 (31.3%) clear fluid and 6 (18.8%) were unsure. Twelve (37.5%) reported becoming sick during delivery, while 20 (62.5%) did not.

4.3 Neonatal-Related Factors

Variable	Category	Frequency	Percentage
Baby cried at birth	Yes	16	50.0
	No	16	50.0
Breech presentation	Yes	2	6.3
	No	30	93.8
Baby born sick	Yes	8	25.0
	No	24	75.0

Sixteen (50.0%) respondents reported that their babies cried immediately after birth and 16 (50.0%) reported that their babies did not. Two (6.3%) reported breech presentation and 30 (93.8%) reported no breech presentation. Eight (25.0%) reported that their babies were born sick, while 24 (75.0%) reported that they were not born sick.

4.4 Health-Facility-Related Factors

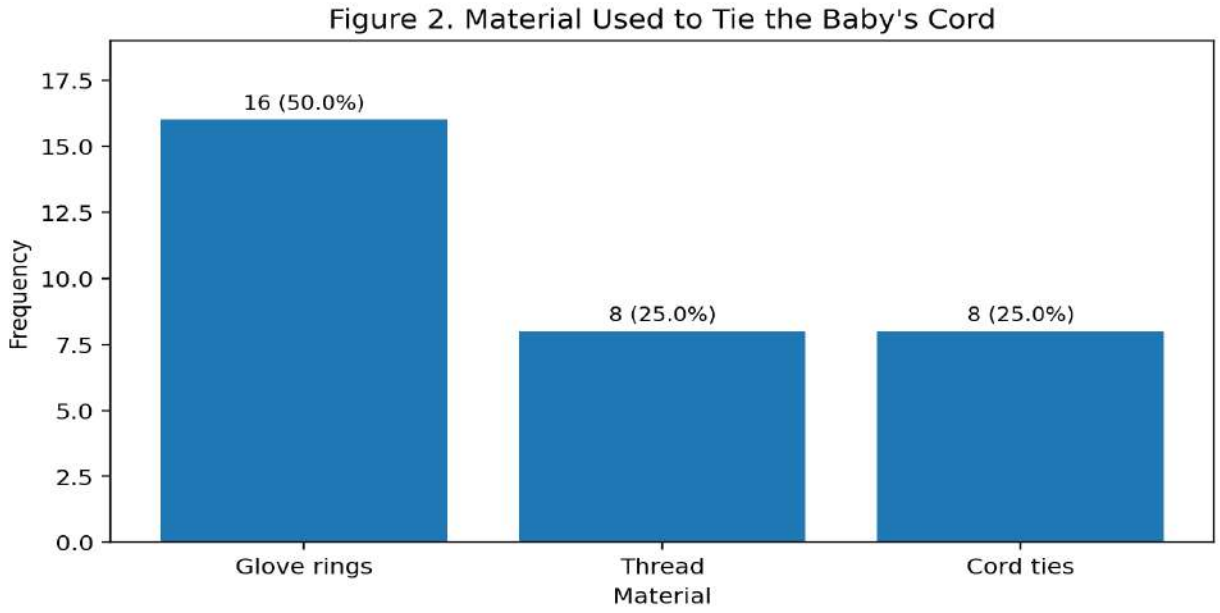
Variable	Category	Frequency	Percentage
Health workers educated mother on cord care	Yes	0	0.0
	No	32	100.0
Health workers washed hands before touching cord	Yes	6	18.8
	No	6	18.8
	Sometimes	20	62.5

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Variable	Category	Frequency	Percentage
Health workers on duty per shift	1–2	30	93.8
	3–4	2	6.3
	5–6	0	0.0
	7 and above	0	0.0

All 32 (100.0%) respondents reported that health workers did not educate them on cord care. Twenty (62.5%) reported that health workers sometimes washed their hands before touching the cord, 6 (18.8%) reported that they did not wash their hands and 6 (18.8%) reported that they did. Thirty (93.8%) respondents reported that one to two health workers were available on the ward per shift, while 2 (6.3%) reported three to four.

Figure 2. Material Used to Tie the Baby's Cord



Sixteen (50.0%) respondents reported use of glove rings, 8 (25.0%) thread and 8 (25.0%) cord ties.

V. DISCUSSION

5.1 Maternal-Related Factors

Although more than half of the respondents reported delivering in a health facility, 12 (37.5%) delivered at home and 2 (6.3%) delivered on the way to a health facility. Home delivery may reduce access to skilled birth attendance and appropriate cord-cutting and cord-care practices. This finding is consistent with literature indicating that home delivery and unhygienic cord practices may increase the risk of neonatal infection [9, 19].

Application of substances to the umbilical cord was common. Vaseline was reported by 14 (43.8%), saliva by 8 (25.0%), breast milk by 4 (12.5%) and cow dung by 3 (9.4%). The finding demonstrates continued use of substances other than recommended cord-care practices. Similar reports from low- and middle-income countries have documented use of petroleum jelly, herbs, saliva, ash and other substances [3, 13].

Antenatal care attendance was also notable. Eighteen (56.3%) respondents attended fewer than four antenatal care visits, compared with 8 (25.0%) who attended four and 6 (18.8%) who attended five or more. Antenatal care provides opportunities for health education, including counselling on newborn and cord care. Merga et al. (2022) similarly highlighted the importance of antenatal care exposure for maternal education on cord care [18].

Half of the respondents reported membrane rupture at delivery, while 25.0% reported rupture before labour and another 25.0% early during labour. Sixteen (50.0%) also reported greenish amniotic fluid. These findings suggest that intrapartum conditions should be considered when assessing newborn infection risk. Previous studies have associated premature rupture of membranes and abnormal or foul-smelling amniotic fluid with neonatal infection [24, 25].

5.2 Neonatal-Related Factors

Half of the respondents reported that their babies did not cry immediately after birth. Although crying at birth is not itself a direct measure of Apgar score, lack of immediate crying may indicate a need for assessment and possible resuscitation. Studies have reported associations between low Apgar scores and neonatal sepsis or morbidity [27, 29].

Breech presentation was reported for 2 (6.3%) neonates. Although the number was small, breech presentation can be associated with birth complications and neonatal morbidity. Roble et al. (2022) included breech presentation among factors considered in neonatal umbilical cord sepsis [30].

Eight (25.0%) respondents reported that their babies were born sick. This may reflect the presence of neonatal illness at birth and reinforces the need for prompt newborn assessment, infection prevention and early management of sick neonates.

5.3 Health-Facility-Related Factors

Hand hygiene was an important reported concern. Twenty (62.5%) respondents stated that health workers sometimes washed their hands before touching the cord, while 6 (18.8%) reported that they did not wash their hands and 6 (18.8%) reported that they did. Hand hygiene is a fundamental component of infection prevention because contaminated hands can transmit microorganisms to vulnerable newborns [34].

Maternal education on cord care was also a major reported gap. All 32 (100.0%) respondents stated that health workers had not educated them on cord care. This finding is particularly important because health workers are an important source of evidence-based information and can address harmful myths and practices. Community and health-worker education has been identified as an important component of improving newborn-care practices [32, 19, 16].

Staffing was another reported concern. Thirty (93.8%) respondents reported that only one to two health workers were available per shift, while 2 (6.3%) reported three to four. Limited staffing may affect the amount of time available for close newborn monitoring, education and adherence to infection-prevention practices. This finding is consistent with literature highlighting the importance of adequate human resources for quality maternal and newborn care [36].

VI. CONCLUSION

The study identified several reported factors that may contribute to umbilical cord infection among neonates admitted to the NICU at Kagando Hospital. Maternal-related factors included home or non-facility delivery, application of substances to the umbilical cord, inadequate antenatal care attendance, membrane rupture and abnormal amniotic fluid. Neonatal-related concerns included failure to cry immediately after birth, breech presentation and illness at birth. Health-facility-related concerns included lack of maternal education on cord care, inconsistent hand hygiene and limited staffing. These findings point to the need for strengthened maternal education, community engagement and infection-prevention practices.

VII. LIMITATIONS OF THE STUDY

The sample size was small, with only 32 respondents, which limits the extent to which the findings can be generalized beyond the study setting.
Purposive sampling was used, which may introduce selection bias.
Several variables relied on respondents' recall and self-report, which may introduce recall or reporting bias.
Limited funding affected the researcher's ability to undertake a larger study.

VIII. RECOMMENDATIONS

The Ministry of Health should strengthen comprehensive education on safe umbilical cord care during antenatal, intrapartum and postnatal care, with particular attention to myths and harmful practices.
Health facilities should provide clear, consistent demonstrations and counselling on evidence-based cord care before mothers and newborns are discharged.
Community health education should be strengthened so that mothers, grandmothers, partners, traditional birth attendants and other influential caregivers receive consistent information on safe cord care.
Health managers should reinforce hand-hygiene compliance and monitor infection-prevention practices in neonatal care areas.
Health-facility management should review staffing levels in neonatal units and advocate for adequate human resources to support close newborn monitoring and quality nursing care.

Community health workers should be equipped with accurate, up-to-date information and appropriate tools to reinforce safe cord-care practices and support early recognition and referral of newborn illness.

Religious and community leaders should be engaged as trusted messengers to address cultural beliefs and practices that may encourage application of unsafe substances to the umbilical cord.

Further studies with larger probability-based samples and stronger analytical designs should be conducted to quantify associations between identified factors and confirmed umbilical cord infection.

IX. NURSING IMPLICATIONS

The findings have important implications for nursing and midwifery practice. Nurses and midwives should treat cord care as an integral part of newborn infection prevention, ensure consistent hand hygiene, provide practical and culturally sensitive education to mothers and caregivers, and identify newborns requiring closer assessment. Health workers should also reinforce early recognition of signs of infection, appropriate referral and timely treatment. At the management level, staffing and availability of infection-prevention supplies should be monitored to support safe neonatal care.

Conflict of Interest

No conflict of interest was reported in relation to this study.

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Dual Stimuli Responsive In-situ Hydrogels for Ocular Drug Delivery Recent Advances Challenges and Future Perspectives

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***Abstract*—Because of the special anatomical and physiological barriers of the eye, such as nasolacrimal drainage, fast tear turnover, and restricted corneal permeability, which together lower the bioavailability of traditional ophthalmic formulations, ocular medication delivery is still a major issue. Because in-situ hydrogels can undergo a sol-to-gel transition in response to physiological stimuli, extending precorneal residence time and improving therapeutic efficacy, they have become viable drug delivery platforms. Because they react to two physiological triggers, such as pH, temperature, or ionic strength, dual stimuli-responsive in- situ hydrogels have drawn a lot of attention among these systems. This allows for better gelation control and more accurate drug release than single stimulus-responsive systems.**

This article offers a thorough overview of dual stimuli-responsive in-situ hydrogels for ocular drug delivery, emphasizing their formulation techniques, polymeric components, design concepts, mechanisms of responsiveness, and assessment parameters. A critical discussion is given of recent developments in the use of these systems to treat ocular conditions such as corneal inflammation, bacterial infections, dry eye syndrome, glaucoma, and allergic conjunctivitis. The benefits of dual-responsive hydrogels are emphasized, including increased ocular retention, better bioavailability, prolonged drug release, and less burst release. Key elements affecting formulation performance and drug release behavior are also investigated.

Polymer compatibility, drug stability, ocular discomfort, tear fluid composition variability, sterilizing requirements, manufacturing scale-up, and regulatory approval are some of the obstacles that still need to be overcome despite their promising promise. Dual-responsive ocular hydrogel systems' clinical translation and commercialization are still hampered by these restrictions.

Future studies are anticipated to concentrate on the creation of sophisticated smart hydrogels, customized eye treatments, AI-assisted formulation design, 3D-printed hydrogel systems, biomimetic and bioadhesive materials, and gene and protein delivery platforms. Dual stimuli-responsive in-situ hydrogels are expected to be a key component of the future generation of ocular drug delivery systems, providing safer, more efficient, and patient-centered therapeutic options, as biomaterials research and pharmaceutical technology continue to progress.

***Index Terms*—Dual stimuli-responsive hydrogels; i- situ hydrogel; stimuli-responsive polymers; allergic conjunctivitis; smart hydrogels**

I. INTRODUCTION

The eye, which has anterior and posterior portions, is an essential element of the human body. One-third of the eye is made up of the anterior segment, which includes the cornea, iris, ciliary body, aqueous humor, and lens. The posterior segment, which includes the sclera, choroid, optic nerve, vitreous humor, and retina, makes up the remaining two-thirds of the eye [1]. Eye drops are often used topical preparations to treat anterior segment disorders. Due to precorneal losses from drainage, fast tear fluid turnover, and dynamics, less than 5% of medications reach the cornea and intraocular tissues following instillation. To increase the bioavailability and retention period of medications, suspensions, emulsions, and ointments are frequently utilized. However, their efficacy is limited by low stability and blurred eyesight. For individuals with chronic conditions including glaucoma and refractory chorioretinal diseases, systemic administration via intraocular injections of medications is preferred because topically applied medications typically do not reach the posterior portion of the eye [2].

Because of induced lacrimation, lacrimal drainage, poor corneal permeability, and the reduced size of the ocular cavity, developing ocular medication delivery systems has always been difficult. Consequently, a dosage form should be able to withstand lachrymal fluid dilution after instillation, not induce discomfort or blurred vision upon instillation, and prolong the drug's duration in the precorneal area [3]. When constructing an ocular pharmaceutical with high therapeutic efficacy, the most important difficulty is to achieve an ideal drug concentration at the site of action.

II. ANATOMY OF EYE

The human eye is made up of several layers with distinct internal structures, each of which serves a particular purpose.

2.1. The Sclera, Cornea, and Conjunctiva

The white portion of the eye that makes up the outer layer of the eye ball and looks as an opaque, rigid white sheath is called the sclera. It maintains the shape of the eye like a rigid fibrous membrane. It continues inside the cornea and is considerably thicker in the back of the eye than in

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the front. It is made up of proteoglycans and collagen fibers that have been incorporated into the extracellular matrix. Because of diffusive transport through the leaky area of collagen fibers, the hydrophilic solutes penetrate the sclera more than the conjunctiva and cornea. Permeability across the sclera is also affected by charges (+/−) on molecules' surfaces. While hydrophilic medicines can diffuse via the ciliary body through the conjunctiva and sclera, the cornea serves as the primary route for topical medication instillation. It provides protection, keeps intraocular pressure stable, and serves as a place where the ciliary muscles can attach [4-5].

The cornea, which is transparent and clear, does not have the blood supply that is located at the front of the eye. It is made up of various components, including the endothelial layers inside, Bowman's membrane, corneal stroma, and corneal epithelium on the outside. The drug's capacity to enter and stay in the aqueous humor depends on the corneal permeability. The corneal epithelium acts as a rate-limiting barrier for the trans-corneal diffusion of lipophilic medicines. A number of ciliary nerves connect the corneal stroma, which is composed of hydrophilic collagen and prevents lipophilic medications from diffusing [6]. Inside the eye, the conjunctiva is a thin, translucent, and delicate epithelial barrier that covers the anterior and one-third of the eyeball and channels inward toward the eyelids. The upper layer, epithelial cells, and their innate substantia propria make up the conjunctiva. With significant electrolyte, fluid, and mucus secretion, the conjunctiva helps form the tear film, which keeps microorganisms out and lubricates the eye cavity. Compared to the cornea, the conjunctiva has a higher surface area and is more drug-permeable. However, the lymphatic and blood capillaries that are pulled into the systemic circulation cause the substantial drug loss. Because of the conjunctival blood cells, capillaries, and tight junctions, which cause excessive drug loss in the systemic circulation and poor ocular drug bioavailability, conjunctival medication absorption is thought to be pointless [6].

2.2. Aqueous Humor

The rear and anterior regions of the eye are filled with this clear, translucent, nonvascular fluid. It transports waste products from nonvascular tissue to the cornea, supplies vital nutrients such sodium, chloride ions, and ascorbate salt, and regulates Schlemm's canal and corneal shape to maintain intraocular pressure. Schlemm's canal is a circular groove that receives aqueous humor from the anterior chamber and delivers it into the bloodstream through the anterior ciliary veins. In humans, the turnover rate of aqueous humor production ranges from 1% to 1.5% of the anterior chamber volume each minute. Aqueous humor forms at a rate of around 2.5 μL/min [7].

2.3. Pupil, Iris, and Ciliary Muscle and Vitreous Humor

The middle of the black portion of the eye is where light enters the chamber. Through an important phenomena known as the light reflex, the pupillary reflex modifies pupil size and shape. The iris is a round, muscular, contractile structure that faces the lens before returning to the cornea. The iris's diaphragm varies in size to regulate the quantity of incident light that enters the eye and to align the pupil size. It is a colorful area of the eye that ranges in color from blue to gray and provides various visual qualities. The ciliary muscle, which controls the passage of aqueous humor

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into Schlemm's canal and eyeshot to objects at suitable distances, is located in the central layer of the eye. The ciliary muscle's contraction or relaxation allows the eye to focus on nearby or far-off objects. Vitreous fluid makes up about 80% of the volume in each human eye. It is located in the chamber that returns to the lens of the eye and appears physically as a transparent substance that looks like jelly [8]. The components of each eye part are shown in detail schematically below (Figure 1).

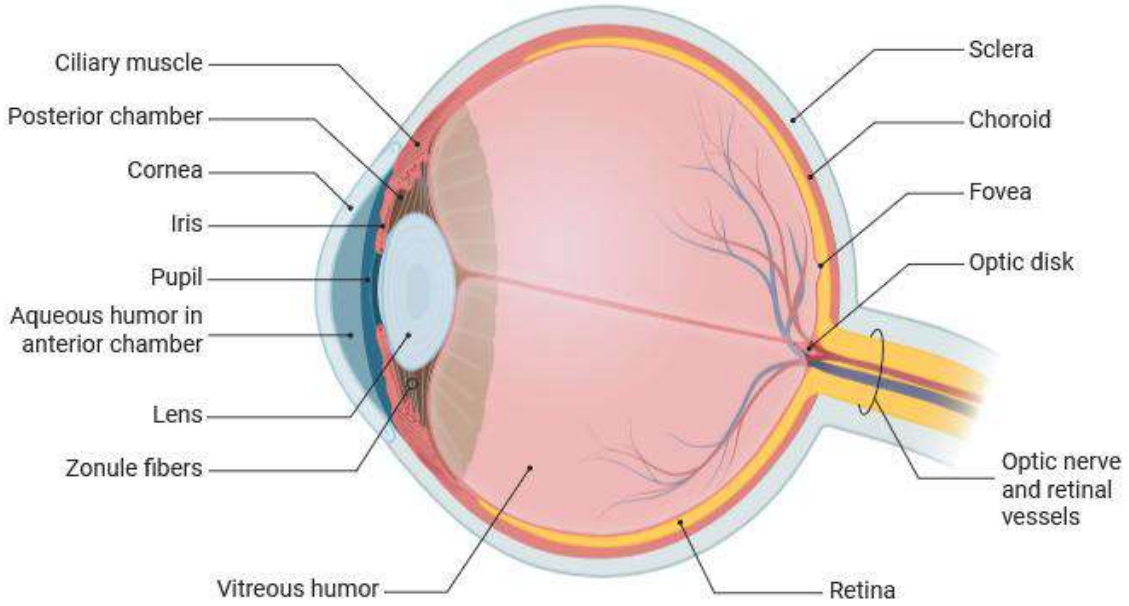


Figure 1. Anatomy of Eye anterior, Created using https://www.biorender.com/

2.4. The Retina, Macula, Choroid, and Optic Nerve

The retina is located on the back of the eye. It is made up of photosensitive rod and cone cells as well as glial, neuronal, vascular, and nerve fibers that transmit light via nerve impulses and go to the brain via the optic nerve. Numerous photoreceptor cells that convert light into nerve signals are found in the macula, which is situated in the middle of the retina.

The macula contains about 200 million neurons and a variety of ganglion cells in its noval structure, a pigmented area close to the center of the retina. The pigment absorbs light and uses the optic nerve to send the light signal to the brain. The brain receives signals from the eye through the optic nerve. The brain then processes the picture data for the central nervous system. Choroids, a thin layer of tissue between the sclera and retina, have blood arteries that provide the eye with nutrition and oxygen while limiting the delivery of medications into the posterior chamber. An optic disk is the front portion of the optic nerve [8].

2.5. Accessory Parts in Eye

The eyebrows, eyelids, lashes, and lacrimal apparatus are some of the components of the eye that shield it from harm. The anterior portion of the eyeball is shielded from dust, pollen, and other

objects by the eyebrow. The delicate cornea and eye front are shielded by the several tissue layers that make up the eyelids and conjunctiva. The lachrymal glands release the tear fluid, which includes water, mineral salts, lysozyme, antibodies, and antibacterial enzymes, when eye drops are applied to the lower conjunctival sac. Upon instillation, the surplus eye drops instantly flow into the gastrointestinal tract through the nasolacrimal system. This could be due to either reflex tearing or the drug dose exceeding the volume of lachrymal fluid. The nasolacrimal drainage system allows the extra volume to enter the digestive system [9-10].

III. BARRIERS IN OCULAR DRUG DELIVERY

The existence of several obstacles is the main cause of the difficulty in achieving appropriate therapeutic dosages within the eye. Before a dose form reaches its site of action, it must overcome a number of challenges, whether it is applied topically or systemically. Ocular bioavailability from topically applied medication is therefore often just 1%–7% of the applied dose. These obstacles fall into two general categories: physiological and anatomical.

3.1 Anatomical barriers

The cornea or the non-corneal pathway are the two ways that a dose form might enter the body when applied topically. Bowman's membrane, endothelium, stroma, descemet's membrane, and epithelium make up the five main portions of the cornea, which is an extremely tight stratified structure. The epithelium serves as the main barrier among them. High paracellular resistance of 12–16 kΩ.cm is produced by these 5–6 layers of columnar epithelial cells with extremely tight connections [11]. It serves as a significant obstacle to the transfer of hydrophilic drugs across intercellular gaps. However, the stroma, which is made up of several layers of hexagonally organized collagen fibers with aqueous pores or channels, functions as a major barrier for lipophilic medications while facilitating the easy passage of hydrophilic pharmaceuticals. Therefore, a medication must have the proper ratio of hydrophilicity to lipophilicity in order to have the best bioavailability. The remaining layers are not very effective barriers and are leaky.

The non-corneal pathway moves via the conjunctiva and sclera, avoiding the cornea. This pathway is crucial, particularly for big, hydrophilic molecules including proteins, peptides, and siRNA [12]. Because the conjunctiva expresses less tight junction proteins than the corneal epithelium, it is more permeable than the cornea, particularly for hydrophilic molecules. Due to the limbal area's high vascularity, a significant portion of the absorbed dose is removed by the blood vessels, making this route unsuitable for drug delivery [13]. The vitreous receives very little of the dosage.

3.2 Physiological barriers

The tear film serves as the eye's main defense. Precorneal variables such solution drainage, tear dilution, tear turnover, and enhanced lacrimation further decrease the bioavailability of topically applied medications [14]. The lacrimal fluid is an isotonic aqueous solution that contains a combination of lipids and proteins, including lysozyme. Lacrimation is much increased after topical application, which causes the dose to be diluted. Drug absorption is then reduced as a result

of the decreased drug concentration. Lacrimation and nasolacrimal drainage and spillage facilitate quick removal from the precorneal region, which further shortens the period that drug molecules are in touch with tissue. Consequently, the precise time for absorption is shortened, resulting in decreased bioavailability. The turnover rate is 16% per minute, and the typical tear volume is 7-9 μL [15]. To avoid severe precorneal loss, medications used as eye drops must be isotonic and non-irritating.

3.3 Pharmacokinetic barriers

The following procedures are indicated by the numbers:[16]

1. Transcorneal penetration into the anterior chamber from the lachrymal fluid,
2. Noncorneal drug penetration into the anterior uvea through the conjunctiva and sclera,
3. Drug delivery enters the anterior chamber from the bloodstream via the blood-aqueous barrier,
4. Drug removal from the anterior chamber through the aqueous humor turnover to Sclemm's canal and the trabecular meshwork,
5. Drug removal through the blood-aqueous barrier from the aqueous humor into the systemic circulation,
6. Drug delivery via the blood-retina barrier to the posterior eye,
7. Intravitreal drug delivery,
8. Drug removal from the vitreous across the blood-retina barrier via the posterior pathway, and
9. The anterior pathway of drug removal from the vitreous to the posterior chamber.

IV. IN-SITU GELLING OCULAR SYSTEMS

Increasing the viscosity of the implanted solution by adding water-soluble polymers is a conventional method of addressing the issue of extending the drug's contact time. The patient population is very receptive to liquid dose forms, such as eye drops. The best delivery system is made up of phase transition polymers that are injected in a liquid state and change to a gel phase once they reach the cul-de-sac of the eye. This allows for sustained medication release and prolonged contact with the cornea of the eye. Improved local bioavailability, lower dose concentrations and frequency, and better patient acceptability might all be attained if a medication's precorneal residence duration could be extended from a few minutes to several hours. These characteristics should be provided by the idea of in-situ gel production.

Longer precorneal residence duration, increased ocular bioavailability, and increased patient acceptability are the goals of ocular drug delivery systems built on the idea of in-situ gel formation. In terms of tissue compatibility, gellan gum, an anionic exocellular polysaccharide derived from microorganisms, and sodium alginate, which has a high glucuronic acid content, are both highly biocompatible and exhibit the distinctive feature of cation-induced gelation.

Conventional liquid ophthalmic formulations (eye drops) exhibit limited bioavailability due to systemic drug absorption, enzymatic metabolism, naso-lachrymal drainage, spillage by overflow, and drug dilution by tear turnover [17].

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4.1 Principle of In-situ Gel

A gelling agent that can create a stable sol/suspension system to hold the dispersed medication and additional excipients is used in the formulation of an in-situ gel system. This sol/suspension solution will gel in the stomach environment as a result of ionic complexation brought on by a pH shift. The formulation used is a sodium alginate or gellan gum solution with calcium chloride and sodium citrate, which complexes the free calcium ions and releases them only in the stomach's acidic environment. As a gelling ingredient, sodium alginate or gellan gum can create textures in the finished product that range from fluid gels to rigid, brittle, non-elastic gels [18]. When free calcium ions become trapped in sodium alginate or gellan gum polymeric chains, the polymer chains crosslink to produce a matrix structure. Double helical junction zones are created during this gelation process, and then double helical segments re-aggregate to form a three-dimensional network through complexation with cations and hydrogen bonding with water [19].

4.2 Advantages

Compared to an already-formed gel, the ability to inject precise and repeatable medication quantities is the main advantage of the in- situ gel. Additional benefits of in-situ forming gel consist of:

- The fewest possible systemic and local adverse effect
- The simplicity of use
- A low dosage is necessary for therapy.
- Enhanced bioavailability
- A decrease in the frequency of drug administration
- It can also be given to unconscious people.
- Enhanced patient comfort and compliance
- increased residence time [20]

4.3 Limitations of Single Stimuli-Responsive Systems

Despite showing great promise for ocular drug administration, single stimuli-responsive in-situ hydrogels (temperature-, pH-, or ion-triggered systems) have a number of drawbacks that could compromise their clinical efficacy. Dual- and multi-stimuli-responsive systems have been developed as a result of these limitations.

4.3.1 Dependence on a Single Physiological Trigger

The gelation of single-responsive hydrogels is triggered by a single environmental stimulus. However, due to the complexity and dynamic nature of ocular physiological parameters, gel formation and drug release may not always be adequately controlled by a single trigger. As a result, the system might not function at its best under different physiological circumstances [21].

4.3.2 Risk of Premature Drug Leakage

Nasolacrimal drainage may remove some of the formulation before gel formation if the quick sol-to-gel transition does not happen right away after instillation. Drug retention and bioavailability may suffer as a result [22].

4.3.3. Need for Higher Polymer Concentrations

To obtain sufficient viscosity and gel strength, single-responsive systems frequently need comparatively high concentrations of gelling polymers. Increased polymer content may result in irritation, impaired vision, ocular discomfort, or decreased patient compliance [23].

4.3.4. Limited Control over Drug Release

It is challenging to precisely modulate gel shape and drug release kinetics since gel formation is controlled by a single stimulus. When compared to dual- or multi-responsive formulations, this could result in less than ideal sustained-release performance [24].

V. SMART OCULAR DELIVERY USING STIMULI-RESPONSIVE IN-SITU GEL PLATFORM

5.1 Thermo-Responsive Thermo-Responsive In-situ Gelling Systems

The most studied stimuli-responsive in-situ gelling systems are thermoresponsive ocular gelling systems. Because of the increased hydrophobicity, this polymeric system experiences a phase transition (solution → gel) in response to temperature changes [25]. To avoid storing the ophthalmic in-situ gel in the refrigerator, where the low temperature could irritate the eyes, it is advised that an ideal thermosensitive in situ gel undergo sol-gel transition upon contact with the eye physiological temperature [6]. Numerous thermo-responsive in-situ techniques have been used to treat a variety of eye conditions, including viral infections, bacterial infections, fungal infections, and glaucoma. The most widely used polymers can be broadly divided into two categories: synthetic polymers (such as poloxamers and poly(N-isopropylacrylamide) or PNIPAAM) and natural polymers (such as cellulose derivatives).

5.2 pH-Responsive In-situ Gelling Systems

The external pH environment is another kind of stimuli-responsive strategy. These polymers are typically polyelectrolytes with repeating units containing basic or acidic groups. When the pH of the surrounding environment rises, weak acidic group polymers (polyacids) exhibit swelling qualities, while weak basic group polymers (polybases) do the same. These polymers' protonation causes electrostatic repulsion and the formation of a network-like matrix, which results in an appearance of swelling and size expansion [8]. These polymers are anticipated to gel when they come into contact with the neutral pH of the ocular surface in the formulation of ocular medication delivery.

5.3 Ion-Responsive In-situ Gelling Systems

The sol–gel transition of ion-responsive in-situ ocular gelling systems, often referred to as ion-activated or ion-sensitive systems, is caused by cross-linking with monovalent (Na+) or polyvalent (Ca2+ and Mg2+) cations in the lachrymal fluids [26-27].

VI.RECENT RESEARCH ON APPLICATION OF MULTI-STIMULI-RESPONSIVE IN-SITU GELLING SYSTEMS

As was previously mentioned, an excellent option for active medication delivery to the administration sites is in situ gel formulation. Having stated that, the body's physiological state, which includes the ocular location, is extremely complex. As a result, in some situations, single-stimuli-responsive in-situ gel formulations might not produce the intended results in drug delivery. The shortcomings of single-stimuli-responsive in-situ gel formulations were addressed by more recent inventions, such as multi-stimuli-responsive in-situ gel formulations, which optimize additional parameters in a more thorough manner. The creation of multi-stimuli-responsive in-situ gel formulations for the treatment of glaucoma, bacterial, fungal, and viral ocular infections, allergic conjunctivitis, and capsaicin-induced eye irritation is the primary focus of this section.

VII. DUAL STIMULI-RESPONSIVE IN-SITU GELLING SYSTEMS

7.1 Concept and Design Principles of Dual Stmuli-Responsive In-Situ Hydrogels

Advanced smart biomaterials called dual stimuli-responsive in-situ hydrogels are made to change from a sol to a gel in response to two different physiological or environmental events. Dual-responsive hydrogels use two complementing stimuli to achieve more precise control over gelation behavior, drug release kinetics, and ocular residency length, in contrast to single stimulus-responsive systems that rely on a single trigger, such as temperature, pH, or ionic strength. Improved therapeutic efficacy is made possible by this dual responsiveness, which has become a viable method for getting around the drawbacks of traditional ocular drug delivery methods, such as quick precorneal drug loss and low bioavailability [28-29].

Adding two stimuli-sensitive polymers or functional groups to a single formulation is the fundamental idea behind dual stimuli-responsive hydrogels. When exposed to physiological ocular conditions, the formulation quickly gels after being injected into the eye as a liquid. In comparison to single-responsive systems, the simultaneous or sequential reaction to several stimuli improves gel formation and retention [30]. Hydrogels that take advantage of the physiological properties of the ocular surface, such as tear fluid pH, ionic composition, and ocular surface temperature, include temperature–pH responsive, temperature–ion responsive, and pH–ion responsive hydrogels [31].

The choice of suitable stimuli that match the visual environment is one of the main design ideas. While pH-responsive polymers like carbopol swell and form gel structures at the physiological tear fluid pH of roughly 7.4, thermoresponsive polymers like poloxamer 407 undergo reversible gelation at ocular surface temperatures (about 34–35°C) [32]. Similar to this, when mono- and

divalent cations found in tear fluid are present, ion-sensitive polymers such sodium alginate and gellan gum undergo ionic cross-linking, which improves gel formation and prolongs retention on the ocular surface [33].

Another important factor to take into account while designing dual-responsive systems is polymer compatibility. In order to produce desired physicochemical qualities without generating instability, precipitation, or phase separation, the chosen polymers should work in concert. While preserving patient comfort, suitable polymer combinations can improve gel strength, viscosity, mucoadhesion, and transparency. For instance, poloxamer–alginate systems use temperature-dependent viscosity increase in addition to ion-induced gelation, whereas poloxamer–carbopol systems combine thermogelation with pH-triggered swelling [29,34].

For ocular use to be successful, gelation characteristics must be optimized. When the formulation comes into contact with the ocular surface, it should quickly turn into a gel while being sufficiently fluid to allow for precise instillation. Additionally, the final gel network should have sufficient mechanical strength to endure blinking and tear drainage while enabling regulated and prolonged medication delivery. These characteristics are greatly influenced by variables such polymer content, molecular weight, cross-linking density, and rheological behavior, which calls for careful optimization [35].

Because improved interaction with the mucin layer can greatly extend precorneal residency time, mucoadhesion is another crucial design criteria. By fostering close contact between the formulation and ocular tissues, the use of bioadhesive polymers reduces medication elimination brought on by nasolacrimal drainage and tear turnover. Thus, increased ocular bioavailability and extended therapeutic effect are facilitated by better mucoadhesion [36].

Throughout the formulation development process, biocompatibility and optical clarity must be preserved. All polymers and excipients used in ophthalmic formulations should be physiologically compatible, non-toxic, and non-irritating because they are applied directly to extremely sensitive ocular tissues. In order to prevent visual disruptions and guarantee patient satisfaction, the hydrogel should also stay transparent following gelation [37].

Dual-responsive systems now provide more design options thanks to recent developments in hydrogel engineering. The creation of multifunctional hybrid delivery systems that can improve drug stability, increase corneal penetration, and provide prolonged drug release has been made possible by the inclusion of nanoparticles, liposomes, micelles, and other nanocarriers within hydrogel matrices. These dual-responsive hydrogels enabled by nanotechnology offer a viable path for the development of next-generation ocular medication delivery systems [38].

In order to accomplish quick gelation, extended ocular retention, regulated drug release, and enhanced patient compliance, dual stimuli-responsive in-situ hydrogels are often designed by carefully combining complimentary stimuli-responsive polymers. These ideas serve as the basis for the creation of sophisticated ophthalmic medication delivery systems that can overcome the main drawbacks of traditional eye drop formulations [28,35].

7.2 Types of Dual Stimuli Systems

7.2.1 pH and temperature-Responsive In-situ Gels

Mono-responsive in-situ gels outperform dual-responsive ones. For instance, in addition to enhanced biological adhesion, mechanical strength, and greater control over drug release, pH and temperature-sensitive gels would be better able to adjust to the physiological complexity [39].

The four stages listed below form the basis for drug release from these matrices:

(a) drug migration and disintegration into adjacent polymers or pores,

(b) drug diffusion due to a gradient in concentration,

(c) drug diffusion to bodily fluids or surrounding media and (d) drug desorption from polymer exteriors [39].

First-order drug release from PF127/TMC/PEG-HA hydrogel, which is made up of pluronic F-127, trimethyl chitosan, and pegylated hyaluronic acid, has demonstrated the advantage of this combination over PF127 alone because TMC and PEG-HA increase contacts between pluronic micelles [40]. Temperature sensitivity was shown by the DOX-loaded CS/HA/GP hydrogel, which changed to a gel form at 37 °C. It has also been demonstrated to release DOX in a pH-dependent manner [41].

Huperzine administered intranasally When exposed to nasal temperature and pH, a loaded TPISG microemulsion (based on 20.80% pluronic F127, 2.8% pluronic F-68, and 0.88% chitosan; creating hup A-M-TPISG) created a mucoadhesive gel that may aid huperzine When compared to parenteral injection, A is delivered through olfactory neurons and avoids the blood-brain barrier (BBB), resulting in a somewhat greater AUCBrain/AUCPlasma [42].

7.2.2 Light and Glucose- Responsive In-situ Gels

In order to overcome unique reactions to conventional medicines, light and glucose responsiveness have been combined in cancer treatment. By combining glucose oxidase (GOx) and gallic acid-ferrous (GA-Fe), which function as glucose and NIR sensitive agents, one of these systems has been proposed. A gel forms at the injection site as a result of GA-Fe's facilitation of temperature rise and enhancement of both parts' catalytic activity upon NIR irradiation. Additionally, the GOx component effectively destroys breast cancer by continually producing hydroxyl radicals and depleting glucose [43].

7.2.3 Dual Light- Responsive In-situ Gels

Various light irradiation causes various reactions in dual light-responsive gels. Dual light responsiveness has been described for the ZPTA-G/HMA platform, which consists of polydopamine-modified zinc oxide (ZP) acting as a photocatalytic material, tannic acid (TA) acting as an anchor moiety, and gelatin-methacrylate hyaluronic acid gel (G/HMA) acting as the scaffold. This mixture has antibacterial properties and can cross-link to the oral mucosa when exposed to green light with a wavelength of 520 nm. However, tannic acid release, zinc oxide photothermal treatment, and the anti-inflammatory action are mediated by NIR irradiation at 808 nm [44].

7.2.4 Temperature and Glucose- Responsive In-situ Gels

Phenylboronic acid (PBA)-based glucose-responsive gels are difficult to inject because they are made of covalent links between PBA and cis-diol groups. On the other hand, temperature-sensitive gels are easy to inject and simply undergo phase change at various temperatures. Therefore, the solution can be administered at room temperature and converted to a gel state at body temperature by incorporating temperature-responsive properties into glucose-triggered gels. This approach has been used in insulin-dispersed alginate-g-P (NIPAM-co-AAPBA) [45]. The gel turns into a solution and releases insulin when the glucose concentration is high, but only a tiny amount of insulin is produced when the glucose level is normal, according to an in vitro examination of this formula. [45].

7.2.5 pH and Glucose- Responsive In-situ Gels

Due to the existence of imine and phenylboronate linkages, DOX-loaded CSPBA/oxidized dextran hydrogel made of modified chitosan with phenylboronic acid and oxidized dextran has demonstrated dual responsiveness to pH and glucose. Because it contains imine and phenylboronate linkages, CSPBA/oxidized dextran quickly changes into a gel state and encapsulates DOX when the pH is raised from an acidic to a physiological level (7.4). Additionally, it was shown that a decrease in pH or an increase in glucose concentration could hasten the release of drug molecules, primarily through diffusion from a swollen matrix [46].

7.2.6 Light and Tempeature- Responsive In-situ Gels

By using the process of light absorption and subsequent temperature raising to cause targeted damage to tumor cells, photothermal therapy has become a promising cancer treatment approach. Using 808 nm NIR irradiation, it was demonstrated that incorporating graphene oxide (GO) or its reduced form (r-GO) into a thermogel made by physically mixing heated agarose and chitosan (thermogel-GO and thermogel-rGO) might induce photothermal therapy against breast cancer cells. This gel demonstrated an antibacterial activity against both gram-positive and gram-negative bacteria due to the presence of chitosan, which was strengthened by NIR irradiation. Because of the increased chitosan dissolution brought on by higher temperatures, the thermogel-rGO antibacterial activity against S. aureus increased by around 12% under NIR irradiation with 1.7 W/cm2 intensity for 10 minutes. Additionally, cell viability was reduced to 34% when doxorubicin: ibuprofen (DOX: IBU) was added to the thermogel-rGO in a 1:5 M ratio [47].

7.2.7 pH and Light- Responsive In-situ Gels

One study used cross-linked carboxymethyl chitosan (CMCS), 2-formylphenylboronic acid (2-FPBA), and epigallocatechin (EGCG) to treat diabetic ulcers by combining pH and light sensitivity. As a multifunctional treatment, the CMCS/2-FBPA/EGCG (CFE) wound dressing hydrogel produced EGCG in response to pH and 808 nm NIR radiation, exhibiting angiogenic and anti-inflammatory effects due to its composition as well as antibacterial activity due to NIR. Spraying natural organic acid might then separate this compound, preventing further damage [48].

Polydopamine-Fe(III)-doxorubicin (PFD) nanoparticles and sodium alginate-graft-dopamine (SD) were synthesized for a study on skin regeneration in melanoma. The resultant doxorubicin-loaded SD/PFD gel demonstrated a synergistic effect in which PFD nanoparticles transformed NIR light into thermal energy. Doxorubicin separated from the SD/PFD gel due to protonation. As a result, doxorubicin was released more readily. Furthermore, the PFD nanoparticles showed catalase-like activity, reducing tumor hypoxia by turning hydrogen peroxide into oxygen [49].

7.2.8 Light and ROS- Responsive In-situ Gels

In addition to producing ROS, photodynamic treatment has the ability to cleave ROS-sensitive linkers, which can further mediate desired hydrogel breakdown and drug release. Adipic dihydrazide-modified hyaluronic acid (HA-ADH) and protoporphyrin IX were conjugated to create a chemo-photo-dynamic cancer treatment. This was followed by covalent coupling with functionalized thioketal (TK-CHO), which is made up of a ROS-triggered TK linker. Under NIR irradiation, this conjugate, known as HA-ADH-PpIX, produced ROS, cleaved the ROS-sensitive linker, and released loaded-DOX. Additionally, it was noted that HA-ADH-PpIX could offer selective therapeutic delivery to targeted areas on demand in addition to extending PpIX delivery [50].

7.2.9. Tempeature and Ion- Responsive In-situ Gels

A dual-responsive system was created by taking into account the ion-sensitivity of Gelrite® and the temperature-responsiveness of pluronic. Gelrite® solution was added to the F-68/F-127 solution to confirm this. The vagina was filled with an optimal formula that contained F-127 18%, F-68 5%, Gelrite® 0.3%, and lidocaine 2%. At vaginal temperature (28 °C), the formulation produced a gel. Prior to IUD implantation, the gel formation maintained the lidocaine release to lessen discomfort [51].

7.2.10 Light and Redox- Responsive In-situ Gels

An injectable CAM-established hydrogel with a reasonable gelation time after injection into the tumor sites was created by functionalizing cartilage acellular matrix (CAM) with norbornene and then combining the resulting CAM-Nb with di-selenide-di-polyethylene glycol-di-tetrazine (DSe-DPEG-DTz) cross-linker. When indocyanine green (ICG) was added to the gels, the solid in-situ gel maintained doxorubicin release under a decreasing state, which was increased by NIR irradiation. Additionally, it might completely eradicate tumors by preventing HT-29 cell metabolic activity after GSH or UV irradiation, such as free doxorubicin with targeted and delayed delivery [52].

VIII. MECHANISM OF DUAL RESPONSIVENESS

Dual stimuli-responsive in-situ hydrogels work because they can change physicochemically in response to two different physiological stimuli. Dual-responsive hydrogels improve therapeutic effectiveness and bioavailability by providing more control over gelation behaviour, swelling

properties, drug release kinetics, and ocular retention as compared to single-responsive systems [53-54]. These systems are specifically made to stay in a low-viscosity solution state while being administered and then change into a gel when exposed to the physiological circumstances of the eyes.

Temperature-pH responsive hydrogels are the most studied dual-responsive technology for ocular medication delivery. When exposed to ocular surface temperatures of roughly 34–35°C, thermosensitive polymers like poloxamer 407 in these formulations undergo a reversible sol-to-gel transition. Polymer chains stay hydrated and readily distributed in solution at lower temperatures. Dehydration of hydrophobic polypropylene oxide segments encourages the creation of micelles and the subsequent development of gel networks as the temperature rises [55]. Concurrently, ionizable carboxyl groups in pH-responsive polymers like carbopol undergo ionization at physiological tear fluid pH (~7.4), which causes electrostatic repulsion between polymer chains and gel network expansion. Gel strength, viscosity, and ocular retention are further improved by this pH-induced swelling [56,29]. As a result, thermogelation and pH-responsive swelling work together to create a hydrogel matrix that is stronger and more stable than either process alone.

The mechanism by which temperature-ion responsive hydrogels function is distinct but complementary. While ion-sensitive polymers like sodium alginate and gellan gum undergo ionic cross-linking in the presence of mono- and divalent cations found naturally in tear fluid, such as sodium, calcium, and magnesium ions, thermoresponsive polymers aid in the formation of gel at physiological temperature [58]. A three-dimensional cross-linked network that improves mechanical stability and extends residence time on the ocular surface is created as a result of the interaction between polymer chains and tear fluid ions. This synergistic reaction promotes extended drug release and increases resistance to nasolacrimal drainage and tear dilution [59].

Ionic cross-linking and polymer ionization occur simultaneously in pH-ion sensitive systems, leading to gel formation. While tear fluid ions reinforce the polymer network through intermolecular ionic interactions, changes in physiological pH cause pH-sensitive polymers to inflate. When compared to single-responsive formulations, the combination of these processes enhances gel integrity and offers more control over drug release behaviour [60].

The performance of dual-responsive hydrogels is significantly influenced by swelling behaviour. Water molecules enter the polymer network after being exposed to physiological stimuli, which causes the hydrogel matrix to expand. Cross-linking density, environmental factors, and polymer makeup all affect how much swelling occurs. While excessive cross-linking may limit drug mobility and extend release duration, increased swelling allows drug molecules to diffuse through water channels inside the gel matrix [54,61]. Therefore, attaining the intended therapeutic results requires careful tuning of swelling features.

Diffusion-controlled and polymer relaxation-controlled processes are typically combined to release drugs from dual stimuli-responsive hydrogels. Drug molecules that are close to the hydrogel surface may first be quickly released into the tear fluid. Diffusion from the inflated polymer matrix and slow relaxation or degradation of the gel network then result in sustained

release [9]. Dual-responsive mechanisms provide more accurate control of these processes, resulting in extended and consistent drug release profiles that improve ocular bioavailability and lower the frequency of dosage [62].

Multifunctional systems that can react to additional stimuli including enzymes, redox conditions, inflammation-associated biomarkers, and external triggers have been made possible by recent advancements in hydrogel engineering. These cutting-edge technologies may be the next generation of intelligent ocular drug delivery platforms since they can further modify drug release behaviour in accordance with disease-specific microenvironments [63].

In general, two separate stimuli-responsive pathways work in concert to control gel formation, swelling, mucoadhesion, and medication release as part of the dual responsiveness process. When compared to traditional ophthalmic formulations and single-responsive hydrogel systems, the synergistic action of these mechanisms greatly improves ocular retention, prolonged drug administration, and therapeutic efficacy [53-54].

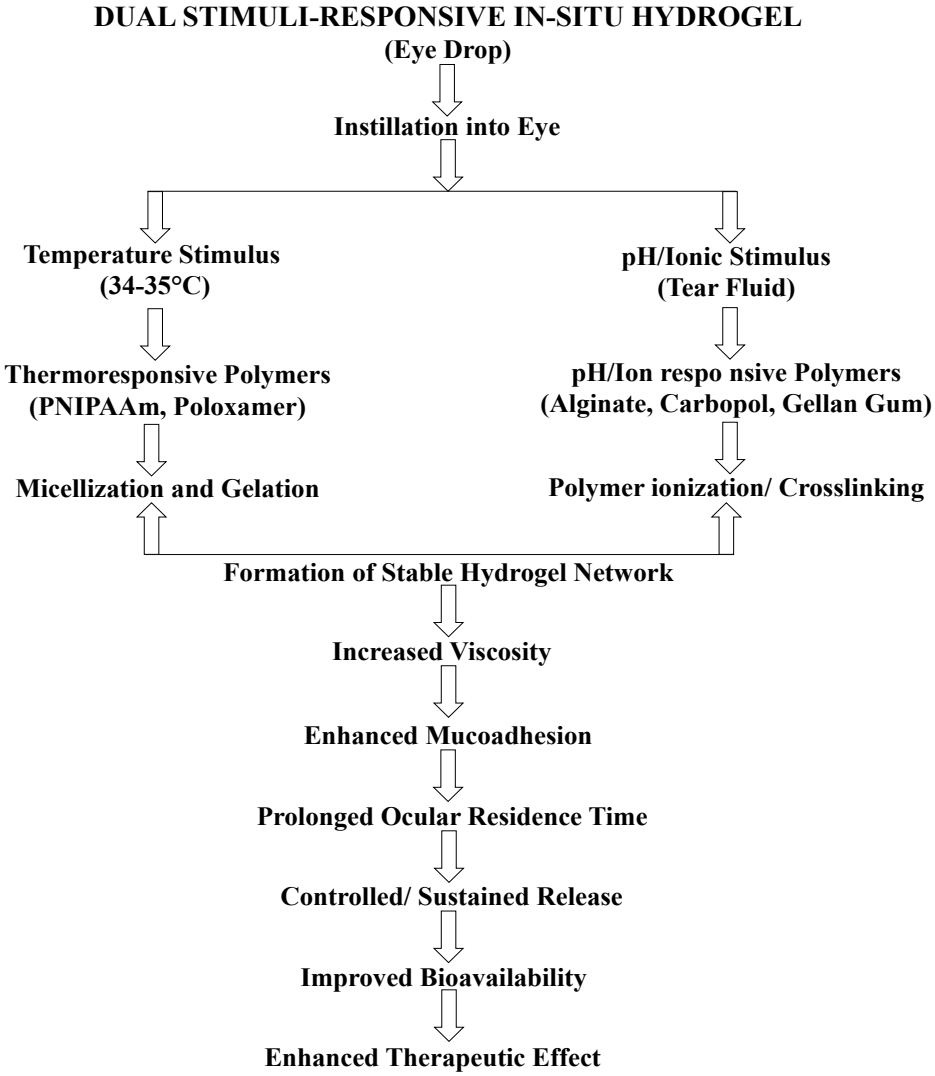


Figure 2. Mechanism of Dual Stimuli-Responsiveness in Ocular In-situ Hydrogels

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IX. ADVANTAGES OF DUAL STIMULI-RESPONSIVE SYSTEMS OVER SINGLE STIMULUS-RESPONSIVE SYSTEMS

By concurrently using two physiological triggers, such as pH, temperature, ionic strength, or enzymes, dual stimuli-responsive in-situ hydrogels provide a number of advantages over traditional single stimulus-responsive systems. In ocular drug delivery systems, the combination of several stimuli improves formulation performance and therapeutic efficacy by giving more control over the sol-to-gel transition process.

9.1 Better Gelation Control

The improved gelation control of dual stimuli-responsive hydrogels is one of their main benefits. Variations in physiological circumstances can cause premature gelation or inadequate gel formation in single stimulus-responsive systems. Dual-responsive systems, on the other hand, produce more consistent and repeatable gel formation as they need two distinct stimuli to fully gel. By reducing formulation instability during injection and guaranteeing quick gelation upon contact with the ocular surface, this dual-trigger mechanism enhances patient compliance and therapeutic efficacy [64].

9.2 Enhanced Ocular Retention

Hydrogels that respond to two stimuli have better precorneal retention than formulations that respond to one stimulus. The formulation's viscosity and mucoadhesive qualities are increased by the stronger and more stable gel network created by the combined action of two physiological triggers. As a result, the hydrogel prolongs the drug's residence duration on the ocular surface by resisting lacrimal drainage and blinking-induced removal. While lowering the frequency of delivery, increased retention improves medication absorption and bioavailability [65-66].

9.3 Improved Sustained Drug Release

Compared to single stimulus-responsive hydrogels, the denser polymeric network produced by dual-responsive systems offers more effective control over drug dispersion. The hydrogel's synergistic reaction to environmental changes can modulate drug release, leading to controlled and extended-release profiles. Sustained drug administration improves treatment outcomes by lowering variations in ocular medication levels and maintaining therapeutic drug concentrations for longer periods of time [67-68].

9.4 Reduced Burst Release

A frequent drawback of many traditional ocular formulations and certain single stimulus-responsive hydrogels is burst release. Due to the tighter and more ordered three-dimensional polymer network that prevents rapid drug diffusion right after delivery, dual stimuli-responsive hydrogels can greatly lessen the initial burst effect. The formulation's safety and effectiveness are improved by the regulated gelation process and increased cross-linking density, which encourage progressive drug release and reduce the possibility of dose dumping [66,68].

X. POLYMERS USED IN DUAL STIMULI-RESPONSIVE OCULAR HYDROGELS

The selection and combination of appropriate polymers that can react to physiological ocular circumstances are critical to the effective development of dual stimuli-responsive in-situ hydrogels. These polymers aid in controlled medication release, mucoadhesion, gel formation, and drug encapsulation. Because of their biocompatibility, responsiveness, and capacity to extend ocular residency length, both natural and synthetic polymers have been thoroughly studied. These polymers work in concert to create sophisticated hydrogel systems that react to various environmental cues while preserving patient comfort and therapeutic effectiveness [31,53].

10.1 Natural Polymers

10.1.1 Sodium Alginate

A naturally occurring anionic polysaccharide, sodium alginate is obtained from brown seaweed. Because of its ion-sensitive gelation characteristics, it is frequently employed in ocular medication administration. Alginate experiences ionic cross-linking and creates a three-dimensional gel network when divalent cations, like the calcium ions found in tear fluid, are present. It is especially helpful in ion-responsive and temperature-ion responsive hydrogel systems because of its characteristic. Additionally, sodium alginate has outstanding mucoadhesive, biocompatible, and biodegradable qualities that support sustained drug release and extended ocular retention [69,58].

10.1.2 Chitosan

Chitosan is a cationic polysaccharide that is produced by deacetylating chitin. Its mucoadhesive and permeation-enhancing qualities are widely recognized. Chitosan's positively charged amino groups interact with the negatively charged mucins on the surface of the eye to extend residence time and enhance drug absorption. Dual-responsive hydrogels often include chitosan to improve ocular permeability, bioadhesion, and gel strength. It is also a good polymer for ophthalmic applications due to its biocompatibility and biodegradability [33,29].

10.1.3 Hyaluronic Acid

A naturally occurring glycosaminoglycan, hyaluronic acid is present in tear fluid and ocular tissues. It has outstanding biocompatibility, hydration capacity, and viscoelasticity. Hyaluronic acid is frequently employed to enhance patient comfort and ocular surface hydration because of its potent water-retaining capacity and lubricating qualities. It reduces eye irritation while increasing viscosity, mucoadhesion, and extended drug retention when paired with stimuli-responsive polymers [70].

10.2 Synthetic Polymers

10.2.1 Poloxamer 407

One of the most popular thermoresponsive polymers for ocular medication administration is poloxamer 407. Polyethylene oxide (PEO) and polypropylene oxide (PPO) segments make up this

triblock copolymer. Poloxamer solutions stay fluid at low temperatures, but dehydration of PPO segments causes micellization and gel formation when exposed to physiological temperature. Poloxamer 407 is commonly used with pH-responsive or ion-responsive polymers to create dual stimuli-responsive ocular hydrogels because of its reversible thermogelation characteristic [32].

10.2.2 Carbopol 934

Cross-linked polyacrylic acid polymer Carbopol 934 is frequently used as a mucoadhesive and pH-responsive substance. Carbopol stays compact at acidic pH levels, but at physiological tear pH, ionization of carboxyl groups results in polymer swelling and gel network expansion. To improve gelation, viscosity, and ocular retention in dual-responsive systems, carbopol is frequently used with thermosensitive polymers like poloxamer 407 [56].

10.2.3 Hydroxypropyl Methylcellulose (HPMC)

HPMC is a semi-synthetic cellulose derivative that is frequently used in ophthalmic formulations as a stabilizer and viscosity enhancer. HPMC is commonly added to dual-responsive hydrogels to enhance gel consistency, lower the critical gelation concentration of thermoresponsive polymers, and control drug release even though it is not intrinsically stimuli-responsive. Patient comfort and ocular residence time are enhanced by its superior biocompatibility and film-forming qualities [37].

10.2.4 Poly(N-isopropylacrylamide) (PNIPAAm)

A synthetic thermoresponsive polymer with a lower critical solution temperature (LCST) around physiological temperature is called PNIPAAm. The polymer experiences a fast phase transition and gel formation above the LCST, while it stays hydrated and soluble below. PNIPAAm has garnered significant interest in the creation of sophisticated temperature-sensitive ocular hydrogel systems due to its acute temperature responsiveness. However, its clinical use has been restricted due to worries about biodegradability and long-term safety [71].

XI. ROLES POLYMER COMBINATIONS

11.1 Gelation

Achieving quick and effective gelation under physiological ocular circumstances is the main goal of mixing various polymers. While carbopol, sodium alginate, and gellan gum contribute to pH-responsive or ion-sensitive gel formation, thermoresponsive polymers like poloxamer 407 give temperature-triggered gelation. Compared to hydrogel networks created by individual polymers alone, the synergistic interaction between these polymers produces stronger and more stable networks [53,56].

11.2 Mucoadhesion

Mucoadhesion is essential for prolonging ocular residence time and decreasing precorneal medication loss. Through hydrogen bonding, electrostatic interactions, and polymer chain

entanglement, polymers such sodium alginate, chitosan, carbopol, and hyaluronic acid interact with the mucin layer of the ocular surface. These interactions enhance formulation retention, which raises the bioavailability of the medicine [33,36].

11.3 Drug Release Modulation

By changing gel structure, swelling properties, and cross-linking density, polymer combinations have a major impact on drug release behavior. While bioadhesive and ion-sensitive polymers govern matrix swelling and drug transport channels, thermoresponsive polymers control gel formation. Dual-responsive hydrogel systems can therefore improve treatment outcomes and patient compliance by minimizing burst release, reducing dose frequency, and providing prolonged and regulated drug release [31,60].

In general, dual stimuli-responsive ocular hydrogels are based on the deliberate blending of synthetic and natural polymers. These polymer systems offer great promise for enhancing the effectiveness of ocular drug delivery and getting around the drawbacks of traditional ophthalmic formulations by combining complementary functions like thermogelation, pH responsiveness, ion sensitivity, mucoadhesion, and controlled drug release.

XII. DRUG INCORPORATION METHODS

Because it directly affects drug loading capacity, formulation stability, release behavior, and therapeutic efficacy, effective drug incorporation is essential to the creation of dual stimuli-responsive in-situ hydrogels. The physicochemical characteristics of the drug, the composition of the polymer, and the desired release profile all influence the drug inclusion technique. To effectively load therapeutic molecules into ocular hydrogel systems while preserving drug stability and responsiveness to physiological stimuli, a variety of techniques have been used [66,35].

Direct drug dissolution is the most straightforward and widely used technique, where the medication is dissolved or evenly distributed throughout the polymeric solution prior to gel formation. After the medication is administered, physiological cues like temperature, pH, or ionic strength create a three-dimensional hydrogel network that traps the drug. This approach is easy to formulate and requires little processing, making it especially appropriate for water-soluble medications. However, because of their quick diffusion from the wet polymer matrix, hydrophilic medications added by direct loading may show an initial burst release [61,65].

Drug suspension or dispersion methods are frequently used for medications that are poorly soluble in water. This method involves evenly distributing micronized medication particles throughout the polymeric solution prior to gelation. The medicine can then gradually dissolve and diffuse into the surrounding tear fluid thanks to the hydrogel matrix's role as a reservoir. This approach can increase drug retention and extend the length of release; however, maintaining physical stability and attaining uniform particle distribution continue to be significant formulation issues [58].

The integration of drug-loaded nanoparticles into hydrogel matrices to create hybrid "nano-in-gel" systems has been the focus of recent developments in ocular drug delivery. Dual-responsive

hydrogels can incorporate nanoparticles, polymeric nanocarriers, nanomicelles, liposomes, niosomes, and solid lipid nanoparticles to improve corneal penetration, preserve labile molecules from degradation, and increase drug encapsulation efficiency. A dual-controlled delivery mechanism is provided by the hydrogel's extended precorneal retention after administration and the nanocarriers' control over drug release [38,72].

Molecular entrapment within the polymer network is another potential strategy. Drug molecules are physically confined within the cross-linked polymer matrix during hydrogel formation by electrostatic, hydrophobic, or hydrogen bonding interactions. Cross-linking density, drug–polymer compatibility, and polymer composition all affect the extent of drug entrapment. This approach is very useful for limiting early medication leakage and attaining sustained release [30].

Encapsulation in carrier systems before hydrogel inclusion is commonly used for sensitive medicinal agents like proteins, peptides, growth factors, and nucleic acids. Microspheres, liposomal systems, and biodegradable nanoparticles can offer an extra line of defense against environmental stress and enzymatic deterioration. By adding these carrier systems to dual-responsive hydrogels, stability is further improved and long-term controlled release of biologics is made possible [73].

A number of formulation factors, including as polymer concentration, cross-linking density, molecular weight, drug solubility, and drug–polymer interactions, affect drug loading efficiency in dual-responsive hydrogels. By creating denser networks, higher polymer concentrations often increase drug entrapment; nevertheless, an excessive polymer content may decrease drug diffusion and have a detrimental impact on syringeability and patient comfort. To balance loading capacity, gelation behaviour, and release performance, formulation parameters must be carefully optimized [74].

Overall, the therapeutic efficacy of dual stimuli-responsive ocular hydrogels is largely dependent on drug inclusion techniques. While sophisticated nano-enabled methods have emerged as potential solutions for enhancing drug stability, bioavailability, and sustained release, conventional drug dissolving techniques are still often employed for small-molecule medicines. The physicochemical properties of the medication and the intended therapeutic goals should be taken into consideration when choosing a loading method [66,38].

XIII. FACTORS AFFECTING DRUG RELEASE FROM DUAL STIMULI-RESPONSIVE HYDROGELS

A number of formulation- and environmental variables affect drug release from dual stimuli-responsive hydrogels. These variables eventually impact treatment efficacy by determining the rate, extent, and mechanism of drug diffusion from the polymeric matrix. Designing hydrogels that can transport drugs to the eyes in a continuous and controlled manner requires an understanding of these factors.

13.1 Polymer Composition and Concentration

Drug release behaviour is greatly influenced by the kind and concentration of polymers employed in hydrogel composition. Increasing polymer concentration typically results in the creation of a denser gel network with smaller pores, which prolongs release and decreases drug diffusion. Additionally, gel strength, swelling behaviour, and release kinetics can be altered by combining polymers with various response properties. For instance, formulations that combine pH-responsive polymers like carbopol with thermoresponsive polymers like poloxamer show improved control over drug release because of synergistic gel formation [56].

13.2 Cross-Linking Density

A key factor in determining the structural characteristics of hydrogels is cross-linking density. By decreasing mesh size and raising diffusion resistance, a heavily cross-linked network limits the mobility of drug molecules. Drug release consequently becomes more gradual and prolonged. On the other hand, hydrogels with less cross-linking density have bigger holes that speed up drug transport and could cause burst release [66,68].

13.3 Swelling Behaviour

Drug release is directly impacted by hydrogel swelling, which controls polymer relaxation and water absorption. Drug molecules can permeate through the wet polymer matrix when hydrogels are exposed to physiological circumstances because they absorb tear fluid and swell. Temperature, ionic strength, pH of the surrounding environment, and polymer composition all affect how much swelling occurs. While minimal edema may delay release, greater swelling typically promotes drug diffusion [67,75].

13.4 Physiochemical Properties of the Drug

Release kinetics are greatly influenced by drug-related variables as molecular weight, solubility, partition coefficient, and drug-polymer interactions. Compared to big or poorly soluble chemicals, small and highly water-soluble molecules diffuse through hydrogel networks more quickly. Strong contacts between the drug and polymer chains may also delay drug diffusion and increase the time of release [76].

13.5 Environmental Stimuli

Environmental triggers including pH, temperature, ionic strength, or enzymatic activity control the responsiveness of dual stimuli-sensitive hydrogels. Drug release can be impacted by changes in various physiological circumstances, which can also change polymer conformation, swelling behaviour, and gel structure. When it comes to ocular drug delivery, concurrent exposure to the pH of tear fluid and the temperature of the ocular surface frequently causes gel formation and regulates the drug's subsequent release [77].

13.6 Hydrogel Degradation and Erosion

Drug release can also happen when the hydrogel matrix erodes or degrades. The structural disintegration and release of confined drug molecules result from the slow hydrolysis or enzymatic degradation of biodegradable polymers. Environmental factors, cross-linking properties, and polymer chemistry all affect the rate of breakdown. Controlled-degradation hydrogels can minimize the requirement for frequent administration while offering extended drug release [31,78].

13.7 Initial Drug Loading

Release kinetics may be affected by the quantity of medication added to the hydrogel. A greater concentration gradient between the hydrogel and the surrounding media is often produced by higher drug loading, which speeds up diffusion. On the other hand, an unwanted initial burst release or drug crystallization could result from excessive drug loading. Therefore, in order to obtain regulated and sustained release characteristics, drug loading optimization is required [67,76].

XIV.RECENT ADVANCES IN DUAL-STIMULI RESPONSIVE IN-SITU HYDROGELS FOR OCULAR DRUG DELIVERY

The creation of dual stimuli-responsive in-situ hydrogels for ocular medication administration has been the subject of extensive research in recent years. These systems provide better gelation characteristics than single stimulus-responsive formulations because they undergo a sol-to-gel transition in response to two physiological triggers, usually temperature, pH, or ionic strength. Precorneal retention is improved, drug release is prolonged, ocular bioavailability is increased, and dose frequency is decreased because to the synergistic effect. Their use in treating a number of ocular conditions, such as allergic conjunctivitis, glaucoma, dry eye syndrome, bacterial infections, and corneal inflammation, has been the subject of recent research [31,75].

14.1 Allergic conjunctivitis

One of the most prevalent ocular hypersensitivity conditions still requiring frequent topical antihistamine medication is allergic conjunctivitis. Dual-responsive hydrogels containing antiallergic medications including olopatadine hydrochloride, ketotifen fumarate, and epinastine hydrochloride have been the subject of recent developments. Formulations that combine pH-sensitive polymers like carbopol 934 with thermosensitive polymers like poloxamer 407 have shown sustained drug release, extended ocular residence time, and quick gel formation upon instillation. By eliminating the need for numerous daily doses while preserving therapeutic drug concentrations on the ocular surface, these methods greatly increase patient compliance [79].

14.2 Glaucoma

Long-term intraocular pressure (IOP) reduction is necessary for glaucoma treatment, however traditional eye drops have limited ocular absorption. Dual stimuli-responsive hydrogels have shown promise as delivery systems for antiglaucoma medications such latanoprost, brimonidine

tartrate, timolol maleate, and dorzolamide hydrochloride. In comparison to traditional ophthalmic solutions, recent formulations based on pH- and temperature-responsive polymer combinations have demonstrated increased corneal contact duration, sustained drug release over several hours, and improved IOP-lowering performance. Drug penetration and therapeutic efficacy have been further enhanced by the addition of nanoparticles to dual-responsive hydrogels [4,80].

14.3 Dry Eye Syndrome

The symptoms of dry eye syndrome include irritation of the ocular surface and instability of the tear film. Dual-responsive hydrogels have been investigated recently for the delivery of lubricants, anti-inflammatory drugs, and tear replacements. Poloxamer, gellan gum, and hyaluronic acid-based thermosensitive and ion-sensitive systems have been shown to prolong ocular surface hydration and improve therapeutic drug retention. By offering constant lubrication and prolonged medication release, these formulations lessen tear deficiency symptoms and enhance eye comfort [81].

14.4 Bacterial Infections

Although topical antibiotics are frequently used to treat conjunctivitis and bacterial keratitis, their efficacy is limited by the quick turnover of tears. Antibiotics like moxifloxacin, ciprofloxacin, gatifloxacin, and ofloxacin incorporated into dual stimuli-responsive hydrogels have demonstrated great potential in getting over these restrictions. Hydrogels that are sensitive to pH and temperature have been shown in recent research to extend the duration of drug residence, preserve effective antimicrobial concentrations at the site of infection, and lower the frequency of dosing. Additionally, when compared to traditional formulations, nanoparticle-loaded dual-responsive systems have demonstrated greater corneal penetration and increased antibacterial efficacy [64].

14.5 Corneal Inflammation

When infection, trauma, surgery, or immune-mediated illnesses cause corneal inflammation, corticosteroids or non-steroidal anti-inflammatory medicines must be administered for an extended period of time. Recently, the delivery of dexamethasone, prednisolone acetate, fluorometholone, and diclofenac sodium has been studied using dual stimuli-responsive hydrogels. These formulations minimize systemic absorption and dosage frequency while delivering anti-inflammatory drugs in a controlled and sustained manner. By ensuring quick gelation upon administration and extended retention on the corneal surface, the combination responsiveness to physiological stimuli improves therapeutic efficacy and lessens ocular discomfort [75,78].

Dual stimuli-responsive in-situ hydrogels are a very promising approach for ocular medication administration, according to recent developments. Compared to traditional ophthalmic formulations and single stimulus-responsive systems, their capacity to react to several physiological triggers allows for fine control of gelation behavior and drug release kinetics (31,75].

XV. CHALLENGES AND LIMITATIONS

Dual stimuli-responsive i- situ hydrogels show great promise for ocular drug delivery, but there are still a number of obstacles to overcome in terms of formulation development, biological performance, manufacturing, and regulatory approval. For these cutting-edge drug delivery systems to be successfully translated into clinical settings and commercialized, these constraints must be addressed.

15.1 Formulation Challenges

15.1.1 Polymer Compatibility

Combining two or more polymers with distinct physicochemical characteristics and responsiveness mechanisms is frequently necessary for the creation of dual stimuli-responsive hydrogels. Because unwanted interactions between polymers can impact gelation behavior, viscosity, transparency, drug loading efficiency, and mechanical strength, achieving good polymer compatibility is a major challenge. Phase separation, instability during storage, and uneven medication release profiles can also result from incompatible polymer combinations. Therefore, to guarantee formulation stability and reproducibility, thorough selection and optimization of polymer blends are required [67,31].

15.1.2 Drug Stability

Another crucial issue is preserving medication stability inside the hydrogel matrix. The chemical stability of integrated medications may be impacted by environmental factors as pH shifts, temperature variations, and ionic interactions. During formulation production and storage, some medications may experience hydrolysis, oxidation, or deterioration. Moreover, drug release behaviour can be changed by interactions between drug molecules and polymer chains, which may lower therapeutic efficacy. Therefore, during formulation development, comprehensive compatibility and stability investigations are necessary [76].

15.2 Biological Challenges

15.2.2 Ocular Irritation

When designing ophthalmic hydrogels, ocular tolerance is a key consideration. Even though biocompatible polymers are typically used in the formulation of dual stimuli-responsive systems, excessive viscosity, improper pH, high polymer concentrations, or residual impurities may result in ocular pain, irritation, obscured vision, or foreign-body sensation upon injection. Prolonged contact of the hydrogel with the ocular surface may also trigger local inflammatory responses in sensitive patients. Therefore, prior to clinical application, biocompatibility and ocular safety assessments are crucial [4,78].

15.2.3 Variable Tear Fluid Composition

Physiological triggers including pH, temperature, and ionic strength affect how well dual stimuli-responsive hydrogels function. However, each person's tear fluid composition is unique and can

be changed by age, illnesses, environmental conditions, or concurrent drugs. Drug release kinetics, swelling properties, and gelation behaviour can all be impacted by changes in tear pH, osmolarity, and electrolyte concentration. Such interpatient variability is a challenge to the creation of formulations that are universally efficacious and may lead to inconsistent therapeutic outcomes [81].

15.3 Manufacturing Challenges

15.3.1 Sterilization

Ophthalmic products must be sterile. However, conventional sterilization methods such as autoclaving, gamma irradiation, or filtration may adversely affect the physicochemical properties of stimuli-responsive hydrogels. Polymer structure, viscosity, gelation temperature, medication stability, and release characteristics can all be changed by exposure to high temperatures or radiation. Thus, choosing a suitable sterilizing technique that preserves formulation integrity and sterility continues to be a major industrial difficulty [75,68].

15.3.2 Scale-up

While several dual-responsive hydrogels show encouraging results in the lab, it is still challenging to translate these formulations into large-scale production. Batch-to-batch consistency, repeatable gelation characteristics, consistent medication distribution, and long-term stability must all be guaranteed by scale-up procedures. Furthermore, it might be difficult and expensive to maintain exact control over polymer composition and processing conditions. These elements might restrict the commercialization and industrial manufacturing of sophisticated ocular hydrogel systems [31,74].

15.4 Regulatory Challenges

15.4.1 Safety Requirements

Ophthalmic drug delivery systems must be thoroughly evaluated by regulatory bodies to prove their quality, safety, and efficacy. The long-term ocular consequences of dual stimuli-responsive hydrogels may not be completely known due to their intricate polymeric networks. Before obtaining clinical licensure, extensive preclinical research is required, including evaluations of ocular irritation, toxicity, biocompatibility, pharmacokinetics, and biodistribution. These specifications lengthen the development process and raise total expenses [56,82].

15.4.2 Clinical Translation

Relatively few dual stimuli-responsive ocular hydrogels have advanced to clinical trials, despite promising preclinical results. Therapeutic results and formulation efficacy may be impacted by variations between human ocular physiology and animal models. Clinical translation may also be delayed by issues with manufacturing scalability, regulatory approval, patient acceptability, and economic viability. In order to successfully move these systems from laboratory research to

clinical practice, future research should concentrate on creating standardized evaluation procedures and clinically relevant models [31,83].

Overall, even though dual stimuli-responsive in-situ hydrogels have several benefits for ocular drug administration, their widespread clinical use and commercial success will depend on resolving formulation, biological, manufacturing, and regulatory issues.

XVI. FUTURE PERSPECTIVE

The limitations of traditional ocular medication delivery systems have been shown to be significantly mitigated by dual stimuli-responsive in-situ hydrogels. It is anticipated that further developments in biomaterials science, nanotechnology, artificial intelligence, and precision medicine would further improve their therapeutic effectiveness despite significant gains in formulation design and preclinical evaluation. In order to provide accurate and long-term eye therapy, future research should concentrate on creating intelligent, patient-specific, and therapeutically translatable hydrogel systems.

16.1 Advances Smart Hydrogels

It is anticipated that the upcoming generation of ocular hydrogels would have several sensitive components that can respond to intricate physiological and pathological cues. Future smart hydrogels might react to biomarkers like enzymes, oxidative stress, glucose levels, inflammatory mediators, or disease-specific molecular signals in addition to pH, temperature, and ionic strength. By enabling on-demand medication delivery in response to illness progression, these devices may increase therapeutic efficacy while reducing needless drug exposure. It is expected that the development of these sophisticated smart hydrogels would heavily rely on the integration of nanotechnology and multifunctional polymers [31,78].

16.2 Personalized Ocular Therapy

A promising strategy for improving treatment results based on unique patient features is personalized medicine. Therapeutic efficacy can be greatly impacted by differences in tear composition, ocular physiology, disease severity, and medication response. Future dual stimuli-responsive hydrogels could be tailored to each patient's needs, enabling personalized control over medication release profiles and gelation behaviour. These customized formulations may enhance therapeutic results and treatment compliance while lowering side effects [84,81].

16.3 AI-Assisted Formulation Design

The development of pharmaceutical formulations is increasingly utilizing machine learning and artificial intelligence (AI) technology. Large datasets can be analysed by these computational methods, which can also forecast the best polymer combinations, drug-polymer interactions, gelation properties, and release kinetics. AI-assisted design has the potential to improve formulation performance while drastically cutting formulation development time and expense. Predictive modelling and digital formulation platforms could speed up the creation of dual stimuli-

responsive ocular hydrogels in the future and enable quick optimization of intricate delivery systems [85-86].

16.4 3D-Printed Ocular Hydrogels

The development of personalized hydrogel-based ocular medication delivery devices is made possible by three-dimensional (3D) printing technology. 3D printing is a desirable method for creating drug-loaded hydrogel constructions and patient-specific ocular implants due to its ability to accurately manage geometry, porosity, drug distribution, and mechanical qualities. 3D-printed stimuli-responsive hydrogels may offer highly regulated and prolonged drug administration while improving patient comfort and therapeutic efficacy, according to recent developments in bioprinting and hydrogel engineering [87-88].

16.5 Biomimetic and Bioadhesive Systems

It is anticipated that hydrogel systems in the future would resemble normal ocular tissues in terms of both structure and function. Biocompatibility and therapeutic efficacy may be enhanced by biomimetic hydrogels that mimic the makeup of tear fluid, mucin layers, and extracellular matrix constituents. Additionally, adding bioadhesive polymers like chitosan, hyaluronic acid, and thiolated polymers can improve ocular retention and enable longer drug residency on the surface of the eye. These advancements could lead to decreased dosage frequency and increased medication bioavailability [89-90].

16.6 Gene and Protein Delivery

Biologics, such as proteins, peptides, antibodies, and nucleic acid-based treatments, are becoming more and more important in emerging eye medicines. However, because to their low stability and restricted ocular penetration, these macromolecules continue to be difficult to distribute. A promising foundation for safeguarding delicate biomolecules and permitting their regulated release at specific locations is provided by dual stimuli-responsive hydrogels. In the future, gene-editing tools, siRNA, mRNA, growth factors, and therapeutic proteins may be included into hydrogel matrices to treat chronic inflammatory illnesses, corneal abnormalities, and inherited retinal diseases [91-92].

16.7 Clinical Translation Opportunities

Relatively few dual stimuli-responsive hydrogel formulations have progressed to clinical review, despite the fact that many have shown promising preclinical results. Large-scale production, long-term safety evaluation, regulatory compliance, and clinical validation should be the main focus of future studies. For clinical translation to be successful, standardized characterization techniques, predictive animal models, and strong quality control systems must be developed. The commercialization of these cutting-edge ocular drug delivery devices may be accelerated by cooperation between pharmaceutical scientists, physicians, biomaterial engineers, and regulatory bodies [74].

In general, the integration of smart biomaterials, customized medicine, artificial intelligence, and sophisticated manufacturing technologies holds the key to the future of dual stimuli-responsive in-situ hydrogels. By offering safer, more efficient, and patient-centered therapeutic solutions for a variety of ocular disorders, these advancements are anticipated to revolutionize ocular drug delivery.

XVII. CONCLUSION

Compared to single stimulus-responsive systems and traditional eye drops, dual stimuli-responsive in-situ hydrogels are a viable platform for ocular medication delivery. These sophisticated hydrogels offer better gelation control, extended precorneal retention, increased ocular bioavailability, sustained drug release, and decreased dose frequency by reacting to two physiological cues, such as pH, temperature, or ionic strength. Dual-responsive formulations for the treatment of a number of ocular conditions, such as allergic conjunctivitis, glaucoma, dry eye syndrome, bacterial infections, and corneal inflammation, have been successfully developed thanks to recent developments in polymer science and hydrogel engineering.

One significant development in ocular drug administration is the capacity of dual-responsive hydrogels to build stable gel networks under physiological settings. Their greater responsiveness and regulated drug release properties minimize drug loss due to nasolacrimal drainage and rapid tear turnover, while also improving therapeutic efficacy and patient compliance. Additionally, the use of biologics, multifunctional polymers, and nanoparticles has increased their potential for long-term and focused ocular therapy.

Despite these encouraging advancements, a number of obstacles still prevent them from being widely used in clinical settings. Polymer compatibility, drug stability, ocular irritation, tear fluid composition fluctuation, sterilization, large-scale production, and regulatory approval continue to be major challenges. Furthermore, the scarcity of clinical data emphasizes the necessity of additional research to determine patient acceptability, long-term safety, and efficacy.

Future studies are anticipated to concentrate on the creation of sophisticated smart hydrogels that can react to various physiological and pathological stimuli, customized eye treatments, AI-assisted formulation optimization, 3D-printed hydrogel systems, biomimetic and bioadhesive materials, and platforms for the delivery of genes and proteins. Dual stimuli-responsive in-situ hydrogels have the potential to revolutionize ocular drug delivery and aid in the creation of more efficient, patient-friendly, and clinically transferable ophthalmic treatments with further interdisciplinary cooperation and technical advancement.

Conflict of interests

The authors declared no conflict of interests.

Author’s Contribution

Conceptualization: Miss. Khushi Sharma; Literature search and data collection: Miss Khushi Sharma; Writing: Miss. Khushi Sharma; Review and drafting: Miss Khushi Sharma; Supervision: Dr. Subhranshu Panda

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List Of Abbreviation

AI	:	Artificial Intelligence
BBB	:	Blood-Brain Barrier
CMCS	:	Carboxymethyl Chitosan
CS	:	Chitosan
DOX	:	Doxorubicin
EGCG	:	Epigallocatechin Gallate
GO	:	Graphene Oxide
GOx	:	Glucose Oxide
HA	:	Hyaluronic Acid
HPMC	:	Hydroxypropyl Methylcellulose
IOP	:	Intraocular Pressure
LCST	:	Lower Critical Solution Temperature
mRNA	:	Messenger Ribonucleic Acid
NIR	:	Near-Infrared
PEO	:	Polyethylene Oxide
PNIPAAm	:	Poly(N-isopropylacrylamide)
PPO	:	Polypropylene Oxide
ROS	:	Reactive Oxygen Species
siRNA	:	Small Interfering Ribonucleic Acid
UV	:	Ultraviolet Radiation

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A Study to Assess the Effectiveness of Health Care Package in Terms of Knowledge, Attitude and Practice on Management of Infertility Among Infertile Women of Selected Hospitals of M.P.

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***Abstract*—Introduction: - Every human being has a right to the enjoyment of the highest attainable standard of physical and mental health. Individuals and couples have the right to decide the number, timing and spacing of their children. Addressing infertility is therefore an important part of realizing the right of individuals and couples to found a family. Infertility and unexpected pregnancies are frequent occurrences. Many couples dream of having children. However, they might not consider concerns related to infertility and rising age while planning a pregnancy. Fertility plays a vital role in a woman's life. In our tradition, fertility is the most important part of marital life. With the fast progression in reproductive medicine and the experiences gained through infertility management, a wider range of treatment options have become available to infertile couples. Need Of the Study: - Infertility is a common clinical problem. It affects 13% to 15% of couples worldwide. The prevalence varies widely, being less in developed countries and more in developing countries where limited resources for investigation and treatment are available. In addition, infertility is considered also a public problem. It does not affect the couples' life only, but it also affects the healthcare services and social environment. The feelings experienced by the infertile couples include depression, grief, guilt, shame, and inadequacy with social isolation. Today, many patients do not receive the recommended medical care that based on the best available evidence. As there is surplus medical information every day that cannot be cached by healthcare providers, clinical guidelines created to endorse *up-to-date* evidence-based practice to improve patients' outcome. Objectives Of the Study: - 1. To assess the pre and posttest knowledge regarding management of infertility**

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among infertile women.2. To assess the pre and posttest attitude regarding management of infertility among infertile women.3. To assess the pre and posttest practice regarding management of infertility among infertile women.4. To assess the effectiveness of health care package on knowledge, practice and attitude regarding management of infertility among infertile women. 5. To find-out the co relation between knowledge, attitude and practice regarding management of infertility among infertile women.6. To find out the association between pretest knowledge, attitude and practice score with selected demographic variable. Methodology: - The researcher adopted a quantitative evaluative research approach were one group pretest and posttest research design were used. A total of 300 infertile women were selected who underwent inclusion criteria to participate in this study. The tool section was categorized on four parts includes demographic variable, structured teaching questionnaire, practice score and attitude scale. A health care package was prepared to impart knowledge and improve attitude and practice among the infertility

***Index Terms*—Infertile women, health care package, management of infertility.**

I. DESCRIPTION ABOUT DEMOGRAPHIC CHARACTERISTICS

In the present study, the socio-demographic data revealed that,

- It was described that majority of 189 (63%) comes belongs to 26-35 years, followed by 76(25.4%) were in age group between 15-25 years and lastly, 35(11.7%) were in age group between 36-45 years.
- It was identified that 114(38%) completed in higher and higher secondary education, followed by 92 (30.6%) had done diploma. Further on, 58(19.3%) had done education primary and secondary level. Lastly, 36(12%) were in graduation and post-graduation.
- The researcher described most of the samples, 124(41.4%) were having income between 50001-15000Rs. It was noted that 84(28.0%) had earning above 30000Rs. Relatively, 64(21.3%) were having income between 15001-30000 and at the end 28(9.3%) were having income below 5000Rs.
- The researcher found that approximately 208(69.3%) belongs to Hindu religion, further on, 56(18.7%) were found to be Muslims. Additionally, 21(7%) found to be Christian and remaining 15(5%) follows other religion.
- The analysis found that 148(49.3%) lives in the rural area,117(39.0%) were in urban area and lastly ,35(11.7%) lives in the semi-urban area.
- The investigator estimated that as per the type of family, it was seen that third –fourth of the samples, 145(48.3%) belongs to the joint family, 78(26%) were in nuclear family and remaining 77(25.7%) resides in the extended family.
- The researcher mentioned that 279(93%), involved in non-consanguineous and remaining found to be consanguineous. This showed the samples were aware about the consequences of consanguineous marriage.
- The investigator reported that among 300 samples, 145(48.4%) found to be common homemaker, followed by 89(29.6%) were engaged in private job, 38(12.7%) were government employee and remaining 28(9.3%) were businessman.

- The researcher remarked that 189(63%) had no habit of physical activities and remaining 111(37%) were engaged in physical activities.
- Out of 300 samples, it was estimated that among 169(56.3%) samples had duration within one year of regular, unprotected intercourse. Further on, 131(43.7%) had infertility issues, after one year of regular of unprotected intercourse.
- The researcher observed that reason for infertility and it has been depicted that 211(70.3%) found the reason due to female infertility and rest 89(29.7%) had male related infertility issues.
- The researcher illustrated that, 146(48.7%), most had the PCOS related problems, followed by 36(12.0%) had thyroid issues. It was also estimated that 28(9.3%) had obesity as one complication, 01(0.3%) faced cancer disease and 89(29.7%) reported they had no co-morbidities.
- The study revealed that 222(74%) had no history, 74(24.7%) verbalizes they do not know about this. 03(1%) reported they had maternal familial issues and 01(0.4%) had paternal history of infertility.
- It was identified that most of the samples, 146(48.7%) had average knowledge regarding management of infertility, followed by 144(48%) had poor knowledge. Relatively, 08(2.7%) had good knowledge and lastly, 02(0.6%). But, after intervention 178(59.3%) were in good category, followed by 64(21.3%) were in average category, 47(15.7%) were in excellent category. It was also reported that 11(3.7%) were found to be in poor category.
- The data analysis stated that out of 300, 121(40.3%) had positive attitude and remaining 179(59.7%) had negative attitude score towards management of the infertility before intervention. Relatively, post attitude score most of the samples, 214(71.3%) had positive attitude and remaining 86(29.7%) had negative attitude towards management of infertility.

It was observed that among 184(61.3%) had poor practice. It was followed by 104(34.7%) had average score and remaining 12(04%) had good level of practice. It was analyzed by the researcher that, almost half of the samples, 134(44.7%) had shifted to average practice followed by 114(38%) had good knowledge and remaining 52(17.3%) remains in the poor category.
Thus, overall, it can be depicted that health care was effective among the infertile women regarding management of infertility.

Therefore, from above conclusion it can be stated that

- RH_1 – There will be significant difference between pre-test and post- test knowledge regarding management of infertility among infertile women at the level of $p \leq 0.05$, is being accepted.
- RH_2 – There will be significant difference between pre-test and post- test attitude regarding management of infertility among infertile women at the level of $p \leq 0.05$, is being accepted.
- RH_3 – There will be significant difference between pre-test and post- test practice regarding management of infertility among infertile women at the level of $p \leq 0.05$, is being accepted.
- RH_4 – There will be significant co-relation between pre-test knowledge, attitude and practice regarding management of infertility among infertile women at the level of $p \leq 0.05$, is being accepted.
- RH_5 – There will be a significant association of pre-test knowledge regarding management of infertility among infertile women at the level of $p \leq 0.05$, is being accepted.

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- RH_6 – There will be a significant association of pre-test attitude regarding management of infertility among infertile women at the level of $p \leq 0.05$, is partially accepted.
- RH_7 – There will be a significant association of pre-test practice regarding management of infertility among infertile women at the level of $p \leq 0.05$, is being partially accepted.

II. RESULTS

It was identified that most of the samples after intervention 178(59.3%) were in good category, followed by 64(21.3%) were in average category, 47(15.7%) were in excellent category. It was also reported that 11(3.7%) were found to be in poor category. Relatively, post attitude score most of the samples, 214(71.3%) had positive attitude and remaining 86(29.7%) had negative attitude towards management of infertility. It was analyzed by the researcher that, almost half of the samples, 134(44.7%) had shifted to average practice followed by 114(38%) had good knowledge and remaining 52(17.3%) remains in the poor category.

III. INTERPRETATION AND CONCLUSION

The data analysis showed that the pre-test knowledge score means and S.D score found to be 7.89 ±2.84 and the posttest knowledge score 19.56±4.12. The mean difference found to be 11.67 at degree of freedom, 299. The “t” value found to be 36.54 which is greater than the tab. Value 2.0, thus clearly shows the effectiveness of health care package found to be seen among the infertile women. Thus, overall, it can be depicted that health care was effective among the infertile women regarding management of infertility.

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Decoding the Rāmāyaṇa Panel of Ellora Cave 16 in the Context of the Vālmīki Rāmāyaṇa

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Abstract—**Indian sculpture represents one of the most significant artistic traditions of the Indian subcontinent, through which religious narratives, philosophical ideas, cultural values, and literary traditions have been transformed into visual forms. Within this rich sculptural heritage, the Kailāsa temple at Ellora Cave 16 occupies a distinctive position, particularly for its extensive representation of themes derived from the Rāmāyaṇa. The Rāmāyaṇa sculptures of the Kailāsa temple provide an important visual interpretation of the epic narrative and demonstrate how a complex literary tradition was translated into a spatial and symbolic sculptural programme.However, the identification and interpretation of individual Rāmāyaṇa scenes at Ellora Cave 16 remain challenging, as the sculptural sequence does not always correspond clearly to a linear narrative. The absence of identifying inscriptions and the condensed visual composition create difficulties in establishing the exact identity of figures and episodes. Therefore, a systematic comparison with the Vālmīki Rāmāyaṇa is required to decode the selected figures and understand their narrative sequence. The present study attempts to decode eight principal figures and narrative scenes of the Rāmāyaṇa panel by examining their iconographic features, gestures, attributes, spatial arrangement, and compositional relationships, and by comparing them with the corresponding episodes in the Vālmīki Rāmāyaṇa. Particular attention is given to the direction of visual reading and to the manner in which individual figures and scenes are arranged to communicate a continuous narrative within the architectural space of the temple. The study also distinguishes between scenes having direct textual parallels in the Vālmīki Rāmāyaṇa and elements that may belong to the wider and evolving Rāmāyaṇa tradition. The study thus highlights the close relationship between literary tradition and visual representation and contributes to a broader understanding of how the Rāmāyaṇa was interpreted and transmitted through the medium of medieval Indian temple sculpture at Ellora.**

Index Terms—**Ellora, Cave 16, Kailāsa Temple, Rāmāyaṇa, Vālmīki, sculpture, iconography.**

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I. INTRODUCTION

The Rāmāyaṇa of Vālmīki is one of the foundational narratives of Indian civilization and has profoundly influenced literature, religion, art and architecture (Goldman et al., 1984–2017; Pollock, 1991). Its story of Rāma, Sītā, Lakṣmaṇa, Hanumān and the conflict with Rāvaṇa has been represented in numerous artistic traditions across India. Among these, the sculptural programme of the Kailāsa temple at Ellora occupies an important position because it transforms a long literary narrative into a sequence of visually recognizable episodes (Michell, 1988; Harle, 1994).

Ellora Cave 16, popularly known as the Kailāsa temple, belongs to the Brahmanical group of the Ellora caves and represents one of the most ambitious achievements of Indian rock-cut architecture (Michell, 1988; Dhaky, 1996). Its extensive sculptural programme includes representations from Hindu mythology and epic traditions. The Rāmāyaṇa reliefs form an important component of this visual programme and provide an opportunity to examine the relationship between Sanskrit literature and medieval Indian sculpture (Cousens, 1926; Harle, 1994).



Fig. 1

The present paper focuses on a selected Rāmāyaṇa sequence consisting of eight principal figures, each containing two, three or four narrative units. The scenes are examined in relation to the

Vālmīki Rāmāyaṇa, with attention to character identification, narrative order, direction of reading and textual correspondence.

II. METHODOLOGY

The study follows a textual and iconographic approach. Each sculptural scene is first identified on the basis of its figures, actions and composition and is then compared with the corresponding episode in the Vālmīki Rāmāyaṇa. References are given according to Kāṇḍa and Sarga, allowing the visual representation to be examined against the literary narrative.

Where an episode corresponds directly to Vālmīki's account, the identification is presented with greater certainty. Where a motif belongs to the broader Rāmāyaṇa tradition or represents an interpretive reading of the sculpture, this is indicated separately. This distinction is particularly important in the case of Hanumān's coiled-tail throne and the interpretation of the palace gateway.

III. RĀMA'S DEPARTURE FROM AYODHYĀ AND THE BEGINNING OF EXILE

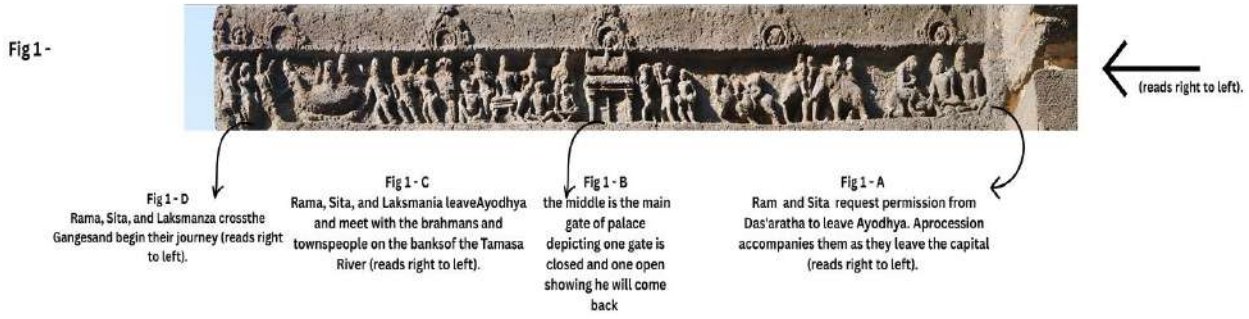


Fig. 1 Rāma's Departure from Ayodhyā and the Beginning of Exile

Fig. 1-A – Rāma, Sītā and Lakṣmaṇa Leave Ayodhyā

The scene depicts Rāma, Sītā and Lakṣmaṇa leaving Ayodhyā, accompanied by members of the royal household and citizens. The composition is read from right to left. The departure marks the beginning of Rāma's fourteen-year exile and the transition from royal life to life in the forest. The episode corresponds to Rāma's departure after accepting Daśaratha's command and his determination to uphold his father's promise. The citizens of Ayodhyā follow him because of their affection for him. (Vālmīki Rāmāyaṇa, Ayodhyākāṇḍa, Sargas 40 and 45)

Fig. 1-B – Palace Gateway

The central architectural element may be identified as the main gateway of the palace. One part of the gateway appears open while another is closed, creating a visual division between the royal space being left behind and the road toward exile. The open and closed gateway may be interpreted symbolically as representing Rāma's departure and his eventual return to Ayodhyā. However, this symbolism is not explicitly described by Vālmīki and should therefore be regarded

as an iconographic interpretation of the sculptural composition. (Vālmīki Rāmāyaṇa, Ayodhyākāṇḍa 40.1–3)

Fig. 1-C – Rāma, Sītā and Lakṣmaṇa at the Tamasa River
The scene depicts Rāma, Sītā and Lakṣmaṇa proceeding toward the Tamasa River, accompanied by Brahmins and citizens. The composition is read from right to left. The presence of the townspeople emphasizes their emotional attachment to Rāma and their reluctance to return to Ayodhyā. The Vālmīki Rāmāyaṇa describes the citizens following Rāma and the party reaching the Tamasa River during the early stage of the exile. (Vālmīki Rāmāyaṇa, Ayodhyākāṇḍa, Sarga 45)

Fig. 1-D – Crossing the Ganges
The scene depicts Rāma, Sītā and Lakṣmaṇa crossing the Ganges, and the composition is read from right to left. The river crossing represents their increasing separation from Ayodhyā and their movement deeper into the forest. The episode corresponds to Rāma's journey to Śṛṅgaverapura, where Guha assists him in crossing the Ganges. Reference: Vālmīki Rāmāyaṇa, Ayodhyākāṇḍa, Sargas 50 and 52.

IV. PAÑCAVAṬĪ AND THE CONFLICT WITH KHARA



Fig. 2 – Pañcavaṭī and the Conflict with Khara

Fig. 2-A – Agastya and Pañcavaṭī
The scene depicts Rāma, Sītā and Lakṣmaṇa meeting the sage Agastya and subsequently settling at Pañcavaṭī. The composition is read from left to right. The sage's presence marks the transition from their wandering through the forest to the establishment of a more permanent dwelling. Agastya directs Rāma toward Pañcavaṭī near the Godāvarī, where Rāma, Sītā and Lakṣmaṇa establish their residence. Reference: Vālmīki Rāmāyaṇa, Araṇyakāṇḍa, Sargas 11–15.

Fig. 2-B – Śūrpaṇakhā and Khara
The scene depicts the mutilation of Śūrpaṇakhā and her subsequent appeal to Khara. The composition is read from left to right. After her encounter with Rāma and Lakṣmaṇa, Śūrpaṇakhā is mutilated by Lakṣmaṇa and approaches Khara seeking revenge. The episode is directly narrated in the Araṇyakāṇḍa. Śūrpaṇakhā's complaint to Khara becomes the immediate cause of

the attack on Rāma and leads to the destruction of Khara's forces. Reference: Vālmīki Rāmāyaṇa, Araṇyakāṇḍa, Sargas 17–19.

Fig. 2-C – Defeat of Khara's Army
The scene represents Rāma's defeat of Khara's army, with the composition read from left to right. The martial grouping of the figures conveys the confrontation between Rāma and the Rākṣasa forces of Janasthāna. The Vālmīki Rāmāyaṇa describes Rāma destroying the Rākṣasa army and subsequently killing Khara. The identification of this relief with the defeat of Khara's forces is also supported by the cataloguing of the Ellora Rāmāyaṇa reliefs. Reference: Vālmīki Rāmāyaṇa, Araṇyakāṇḍa, Sargas 23–30.

Fig. 3 – The Golden Deer and Abduction of Sītā

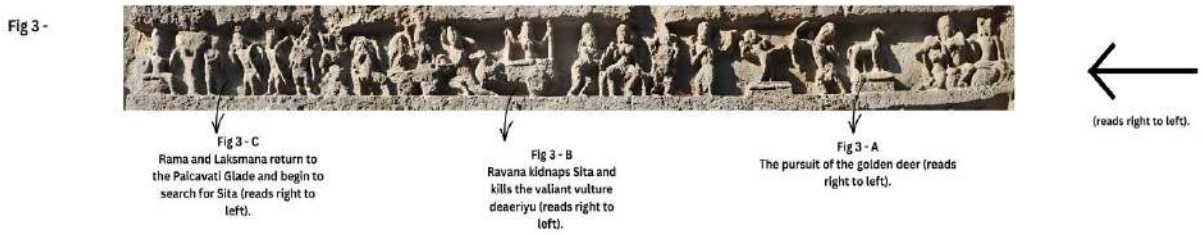


Fig. 3 – The Golden Deer and Abduction of Sītā

Fig. 3-A – The Golden Deer
The scene depicts Rāma pursuing the golden deer, and the composition is read from right to left. The extraordinary deer attracts Sītā's attention, leading Rāma to pursue it into the forest. The deer is actually the demon Mārīca, who assumes the form of a magnificent golden deer at Rāvaṇa's request. Rāma pursues and eventually kills him. Reference: Vālmīki Rāmāyaṇa, Araṇyakāṇḍa, Sargas 42–44.

Fig. 3-B – Rāvaṇa, Sītā and Jaṭāyu
The scene depicts Rāvaṇa abducting Sītā and Jaṭāyu attempting to rescue her, and the composition is read from right to left. Rāvaṇa carries Sītā away from the forest dwelling, while Jaṭāyu intervenes and fights to prevent her abduction. The episode is directly described in the Vālmīki Rāmāyaṇa. Jaṭāyu fights courageously but is ultimately mortally wounded by Rāvaṇa. Reference: Vālmīki Rāmāyaṇa, Araṇyakāṇḍa, Sargas 47–51.

Fig. 3-C – Rāma and Lakṣmaṇa Search for Sītā
The scene depicts Rāma and Lakṣmaṇa returning to the Pañcavaṭī area and beginning their search for Sītā. The composition is read from right to left. Rāma discovers Sītā's absence and searches the forest with Lakṣmaṇa. The brothers eventually encounter the dying Jaṭāyu, who informs Rāma that Rāvaṇa has abducted Sītā. Reference: Vālmīki Rāmāyaṇa, Araṇyakāṇḍa, Sargas 54–60.

V. SUGRĪVA, VĀLI AND THE RESTORATION OF KIṢKINDHĀ

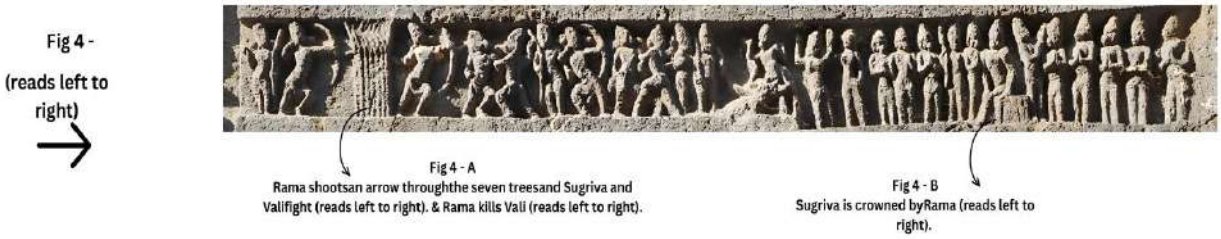


Fig. 4 – Sugrīva, Vāli and the Restoration of Kiṣkindhā

Fig. 4-A – The Seven Trees, Sugrīva–Vāli Combat and Death of Vāli
The scene combines Rāma's demonstration of his strength by shooting through the seven trees, the combat between Sugrīva and Vāli, and the death of Vāli. The composition is read from left to right. These episodes establish Rāma's alliance with Sugrīva and the restoration of Sugrīva's position in Kiṣkindhā. The Vālmīki Rāmāyaṇa describes Rāma's demonstration of strength and his subsequent killing of Vāli during the second combat between the brothers. Reference: Vālmīki Rāmāyaṇa, Kiṣkindhākāṇḍa, Sargas 11–17.

Fig. 4-B – Sugrīva's Coronation
The scene represents Sugrīva's restoration as king of Kiṣkindhā, and the composition is read from left to right. The episode marks the fulfilment of Rāma's promise to Sugrīva following Vāli's death. For textual accuracy, the scene should not be described as "Rāma crowns Sugrīva." Rāma facilitates Sugrīva's restoration but remains outside Kiṣkindhā because of his exile. Sugrīva becomes king and Aṅgada is appointed crown prince. Reference: Vālmīki Rāmāyaṇa, Kiṣkindhākāṇḍa, Sargas 18 and 27.

VI. THE SEARCH FOR SĪTĀ AND HANUMĀN'S JOURNEY

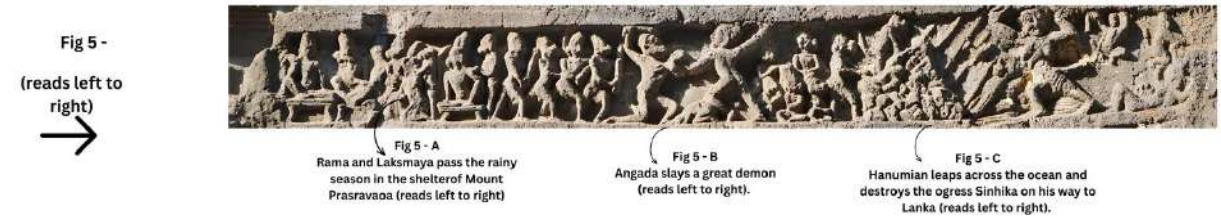


Fig. 5 – The Search for Sītā and Hanumān's Journey

Fig. 5-A – Rāma and Lakṣmaṇa at Mount Prasravaṇa
The scene depicts Rāma and Lakṣmaṇa spending the rainy season at Mount Prasravaṇa, and the composition is read from left to right. The rainy season delays the beginning of the search for Sītā and creates a temporary pause in the narrative. The Kiṣkindhākāṇḍa describes Rāma's

emotional condition during the rainy season and his expectation that Sugrīva will begin the search after the rains. Reference: Vālmīki Rāmāyaṇa, Kiṣkindhākāṇḍa, Sargas 28–30.

Fig. 5-B – Aṅgada and a Demonic Figure

The scene depicts Aṅgada confronting a powerful demonic figure, and the composition is read from left to right. The episode may be connected with the activities of the southern search party led by Aṅgada. However, the identification of a specific "great demon" being slain by Aṅgada cannot be established with sufficient certainty from the Vālmīki text. It is therefore preferable to describe the figure cautiously as Aṅgada confronting a demonic figure. Reference: Vālmīki Rāmāyaṇa, Kiṣkindhākāṇḍa, Sargas 41–53.

Fig. 5-C – Hanumān Crosses the Ocean

The scene depicts Hanumān's leap across the ocean and his encounter with Siṃhikā, and the composition is read from left to right. Hanumān begins his journey toward Laṅkā and encounters Siṃhikā, who captures his shadow. Hanumān defeats Siṃhikā and continues his journey toward Laṅkā. The episode is clearly described in the Sundarakāṇḍa. Reference: Vālmīki Rāmāyaṇa, Sundarakāṇḍa, Sarga 1.

VII. HANUMĀN IN LAṄKĀ

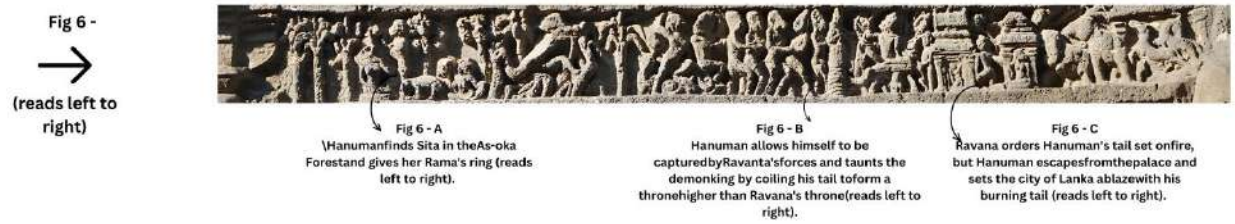


Fig. 6 – Hanumān in Laṅkā

Fig. 6-A – Hanumān Meets Sītā

The scene depicts Hanumān finding Sītā in the Aśoka grove and presenting Rāma's ring to her, and the composition is read from left to right. Hanumān identifies himself as Rāma's messenger and uses the ring as a sign of his authenticity. Sītā recognizes the ring and receives assurance that Rāma is searching for her. Reference: Vālmīki Rāmāyaṇa, Sundarakāṇḍa, Sargas 33–36.

Fig. 6-B – Hanumān Before Rāvaṇa

The scene depicts Hanumān being captured and brought before Rāvaṇa, and the composition is read from left to right. Hanumān deliberately creates an opportunity to enter Rāvaṇa's court and boldly communicates Rāma's message. The Vālmīki Rāmāyaṇa describes Hanumān's appearance before Rāvaṇa and his fearless speech. However, the specific motif of Hanumān forming a throne from his coiled tail and sitting higher than Rāvaṇa is not found in Vālmīki's account and

should be treated as a later or broader Rāmāyaṇa tradition. Reference for the Vālmīki episode: Sundarakāṇḍa, Sargas 47–52.

Fig. 6-C – Burning of Laṅkā

The scene depicts Rāvaṇa ordering Hanumān's tail to be set on fire, followed by Hanumān's burning of Laṅkā. The composition is read from left to right. Hanumān transforms the punishment imposed upon him into an opportunity to attack the city. After escaping his captors, Hanumān moves through Laṅkā with his burning tail and sets buildings ablaze before returning toward Sītā. Reference: Vālmīki Rāmāyaṇa, Sundarakāṇḍa, Sargas 52–54.

VIII. THE BRIDGE AND THE WAR IN LAṄKĀ

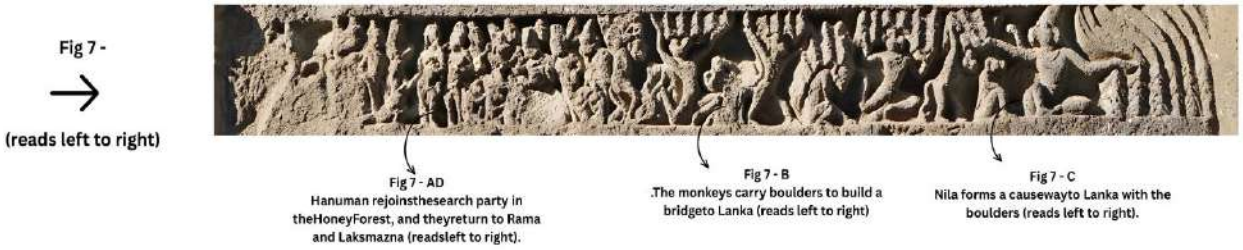


Fig. 7 – The Bridge and the War in Laṅkā

Fig. 7-A – Hanumān Returns with the News of Sītā

The scene represents Hanumān rejoining the southern search party after his successful mission to Laṅkā, and the composition is read from left to right. Hanumān reunites with Aṅgada, Jāmbavān and the other vānaras, after which they proceed toward Rāma to report the discovery of Sītā. The vānaras celebrate their success at Madhuvana before returning to Rāma. Hanumān then gives Rāma the account of his meeting with Sītā. Reference: Vālmīki Rāmāyaṇa, Kiṣkindhākāṇḍa, Sargas 61–67.

Fig. 7-B – Vānaras Carry Stones and Boulders

The scene depicts the vānaras carrying stones, boulders and trees toward the ocean for the construction of the bridge to Laṅkā. The composition is read from left to right. The large number of figures emphasizes the collective effort required for the construction of the causeway. The Vālmīki Rāmāyaṇa states that the vānaras bring trees, rocks and stones for the construction of the bridge. The work is organized under Nala's direction. Reference: Vālmīki Rāmāyaṇa, Yuddhakāṇḍa, Sargas 22–23.

Fig. 7-C – Nala Constructs the Causeway

The scene depicts Nala directing the construction of the causeway across the ocean, and the composition is read from left to right. The vānaras transport and place the materials while Nala undertakes the principal task of constructing the bridge.

The Vālmīki Rāmāyaṇa specifically identifies Nala, the son of Viśvakarmā, as the builder of the bridge. This identification should be distinguished from Nīla, who appears later as a warrior in the battle against Prahasta. Reference: Vālmīki Rāmāyaṇa, Yuddhakāṇḍa, Sargas 22–23.

IX. THE VĀNARA ARMY AND THE WAR IN LAṄKĀ

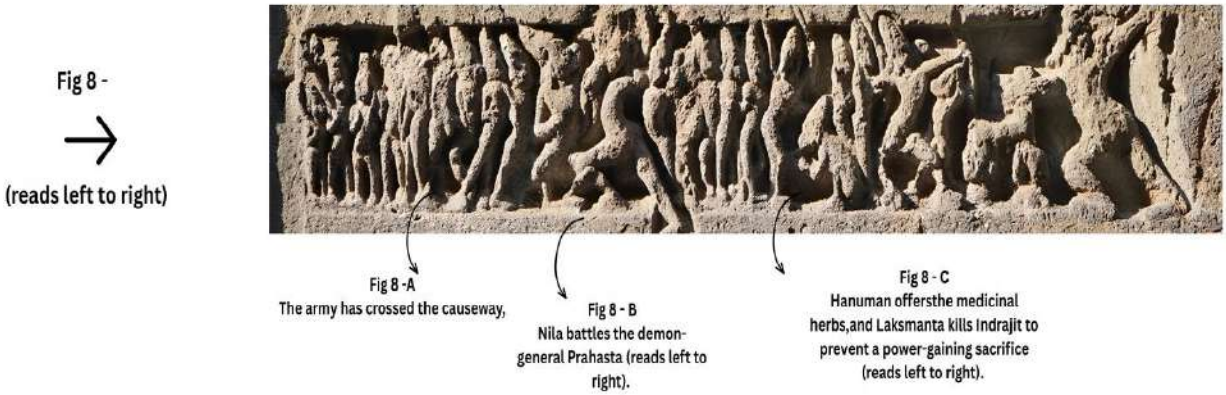


Fig. 8 – The Vānara Army and the War in Laṅkā

Fig. 8-A – The Army Crosses the Causeway
The scene depicts Rāma's vānara army crossing the causeway toward Laṅkā. The composition represents the continuation of the military expedition following completion of the bridge. The crossing transforms the ocean from a natural barrier into a route for Rāma's army. The episode corresponds to the Yuddhakāṇḍa, where the bridge is completed and the army crosses toward Laṅkā to begin the final campaign against Rāvaṇa. Reference: Vālmīki Rāmāyaṇa, Yuddhakāṇḍa, Sargas 22–26.

Fig. 8-B – Nīla Battles Prahasta
The scene depicts Nīla battling Prahasta, the chief commander of Rāvaṇa's army, and the composition is read from left to right. The confrontation represents one of the major engagements between the vānara and Rākṣasa forces. Nīla ultimately kills Prahasta in battle, thereby weakening the military leadership of Laṅkā. Reference: Vālmīki Rāmāyaṇa, Yuddhakāṇḍa, Sarga 46.

Fig. 8-C – Hanumān and the Medicinal Herbs; Lakṣmaṇa and Indrajit
The scene combines Hanumān's bringing of the medicinal herbs and Lakṣmaṇa's final battle with Indrajit, and the composition is read from left to right. Hanumān brings the medicinal herbs after Lakṣmaṇa is severely wounded, while the later portion of the scene relates to Indrajit's Nikumbhilā ritual and Lakṣmaṇa's subsequent battle with him. According to the Vālmīki Rāmāyaṇa, Hanumān brings the mountain containing the medicinal herbs to restore the wounded warriors. Later, Lakṣmaṇa interrupts Indrajit's Nikumbhilā ritual and engages him in battle, ultimately killing him. Reference: Vālmīki Rāmāyaṇa, Yuddhakāṇḍa, Sargas 74–77 and 80–87.

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X. CONCLUSION

The Rāmāyaṇa panel of Ellora Cave 16 presents a condensed yet remarkably extensive visual narration of the epic. The eight figures examined in this study collectively cover the principal stages of Rāma's story: departure from Ayodhyā, forest exile, the abduction of Sītā, alliance with Sugrīva, Hanumān's search, the discovery of Sītā, the burning of Laṅkā, construction of the bridge and the war against Rāvaṇa's forces.

The comparison with the Vālmīki Rāmāyaṇa demonstrates that most of the principal identifications have clear textual parallels. At the same time, the sculpture should not be regarded as a literal illustration of every verse. The sculptor selected visually powerful episodes and compressed lengthy narrative passages into recognizable compositions. In several cases, one sculptural unit represents more than one event, while architectural elements and gestures provide additional narrative meaning.

The study also demonstrates the importance of distinguishing between textual evidence and iconographic interpretation. The identification of Nala as the bridge-builder and Nīla as the warrior who battles Prahasta is particularly important. Similarly, the coiled-tail throne of Hanumān should be recognized as a motif of the broader Rāmāyaṇa tradition rather than directly attributed to Vālmīki. Such distinctions strengthen the reliability of the interpretation.

The Ellora panel may therefore be understood as a visual re-narration of the Vālmīki Rāmāyaṇa. Through the selective arrangement of figures, gestures, architecture and dramatic actions, the sculptural programme transforms the Sanskrit epic into a spatial narrative accessible through visual observation. The panel consequently provides valuable evidence for understanding not only the continuity of the Rāmāyaṇa tradition but also the manner in which medieval Indian artists interpreted, condensed and transmitted epic literature through sacred art.

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Monte Carlo-Optimized Tensile Strength and Stiffness of Mapp-Enhanced Polypropylene (PP)/Palm Kernel Shell Powder (PKSP) Bio Composites for Rigid Food Packaging Application

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***Abstract*—The pressing environmental challenges posed by conventional petroleum-derived plastics have accelerated the exploration of sustainable alternatives, particularly biocomposites derived from agricultural waste. This investigation focuses on the development and performance optimization of a rigid biocomposite material composed of polypropylene (PP) reinforced with palm kernel shell powder (PKSP) a readily available lignocellulosic byproduct of the palm oil industry. The target application is rigid food service and packaging products such as plates, trays, cups, containers, and lids. PKSP underwent comprehensive characterization prior to composite fabrication with maleic anhydride-grafted polypropylene (MAPP) enhanced PP. Composite specimens measuring 15 mm × 15 mm × 100 mm were produced through melt mixing followed by compression molding, with PKSP concentrations ranging from 5 wt% to 25 wt% across three particle size fractions: 75 µm, 250 µm, and 500 µm. Tensile properties, specifically strength and modulus, were rigorously assessed using an electronic Universal Testing Machine (UTM-YYL016) in accordance with ASTM protocols. Monte Carlo optimization algorithms, executed through custom Python programming, were subsequently applied to identify the optimal particle size and loading combinations that maximize mechanical performance. The analysis yielded three distinct optimized formulations: (75 µm, 25 wt%) offering the most favorable strength-stiffness balance at 166.77 MPa·GPa; (75 µm, 5 wt%) exhibiting peak tensile strength of 35.60 MPa; and (500 µm, 25 wt%) demonstrating maximum tensile stiffness of 5.64 GPa.**

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Experimental outcomes reveal that PKSP incorporation markedly improves composite stiffness, accompanied by a modest, acceptable decline in tensile strength a characteristic behavior in particulate-filled systems. These findings substantiate PKSP as an economically viable, environmentally sustainable reinforcing agent for polypropylene, thereby confirming its practical applicability in rigid food packaging. This work contributes meaningfully to agricultural residue valorization, fosters circular economic models, and promotes the advancement of eco-friendly polymeric materials for packaging applications.

Index Terms—**Polypropylene (PP), palm kernel shell powder (PKSP), Maleic Anhydride-grafted Polypropylene (MAPP), bio-composite, natural filler, mechanical properties, compatibilizer, compression molding, optimization, sustainable materials, food packaging, waste Valorization, greener materials.**

I. INTRODUCTION

Growing anxieties over the environmental toll exacted by the widespread utilization of petroleum-derived plastics have catalyzed an intensification of research efforts directed toward sustainable material alternatives, with the food packaging sector emerging as a primary focal point [11]. Although traditional plastic packaging materials demonstrate commendable mechanical robustness and effective barrier characteristics, they pose considerable ecological threats owing to their reliance on finite fossil resources and their resistance to natural degradation processes [11]. The accumulation of plastic refuse substantially compounds environmental deterioration, as enormous quantities of packaging waste ultimately find their way into landfills and natural ecosystems [11]. The challenges associated with managing plastic waste at the conclusion of its useful life, coupled with escalating production rates and increasingly brief utilization windows, have emerged as pressing concerns necessitating prompt remedial action [19]. This heightened awareness regarding plastic pollution has stimulated substantial interest in the creation of packaging materials derived from renewable biological resources that offer enhanced environmental compatibility [19].

Natural fiber-reinforced polymer composites (NFRPCs) have positioned themselves as attractive substitutes for traditional synthetic materials, affording the simultaneous advantages of diminished ecological footprint and superior material characteristics [8]. These bio-based composites constitute a distinctive category of materials produced through the combination of a polymeric matrix with natural fiber reinforcements, capitalizing on the inherent biodegradability and adaptable attributes of natural fibers whilst preserving the desirable processing characteristics of thermoplastic polymers [15]. Contemporary scholarly assessments have thoroughly catalogued the promise exhibited by diverse natural fibers among them jute, sisal, hemp, bamboo, and kenaf as environmentally responsible reinforcing agents suitable for composite fabrication and packaging applications [12]. Lignocellulosic fibers have drawn considerable research attention owing to their modest density, minimal abrasive tendencies, and favorable inherent mechanical attributes [12]. Additionally, the reprocessing and repurposing of agricultural byproducts into composite materials

serves the dual purpose of reducing material costs and advancing sustainability objectives and circular economic frameworks [17].

Within the extensive array of agricultural residual materials amenable to composite reinforcement, palm kernel shell (PKS) has attracted noteworthy scholarly interest as a particularly advantageous filler candidate [5]. PKS represents an abundant secondary product arising from the conversion of palm kernels into edible oil, offering an economical, lightweight, and renewable substitute for traditional inorganic fillers including basalt, graphite, mica, and aluminum magnesium silicate [1]. The deployment of PKS as a reinforcing agent simultaneously addresses two pressing sustainability imperatives: the beneficial repurposing of agricultural discards and the diminished dependence on exhaustible mineral resources [17].

Prior scholarly investigations concerning PKS-reinforced polypropylene (PP) composites have laid essential groundwork concerning their mechanical response characteristics [9]. Experimental evidence indicates that the introduction of PKS as a filler typically produces enhanced tensile and flexural moduli within the PP matrix, although these improvements are frequently accompanied by diminished tensile strength, flexural strength, and elongation at fracture [1]. Systematic studies have documented decreases in tensile strength, flexural strength, and elongation at break corresponding to incremental increases in filler concentration, whilst tensile modulus, flexural modulus, and moisture uptake exhibited upward trends [17]. Microscopic examination employing scanning electron microscopy (SEM) has disclosed inadequate interfacial bonding between PKS particulates and the PP matrix as filler content escalates, attributable to the fundamental incompatibility existing between hydrophilic lignocellulosic materials and hydrophobic polymeric matrices [9]. This interfacial deficiency constitutes a primary obstacle in the advancement of natural fiber composite technologies [7]. The influence of filler particle dimensions on composite performance characteristics has likewise been scrutinized, with findings indicating that micro-scale filler systems exhibit superior tensile strength under conditions of optimized filler loading [20]. Furthermore, investigations into composites incorporating diverse agricultural waste fillers have verified that materials containing agro-waste components display enhanced stiffness relative to unmodified PP matrices achieving improvements of up to 49% alongside elevated tensile strength, though these gains are realized at the expense of reduced ductility [17].

Various compatibilization methodologies have been investigated as potential solutions to the interfacial adhesion difficulties inherent in natural fiber composites [7]. Maleic anhydride-grafted polypropylene (MAPP) has established itself as one of the most efficacious coupling agents for promoting compatibility between natural fillers and PP matrices [9]. The maleic anhydride functional groups present in MAPP establish hydrogen bonds with hydroxyl moieties situated on the natural filler surface, whilst the polypropylene backbone maintains compatibility with the PP matrix, thereby forming covalent connections that strengthen interfacial bonding [7].

Research findings consistently affirm that MAPP incorporation substantially improves the mechanical performance of natural fiber-reinforced PP composites [9]. In particular, PP-g-MAH compatibilizer has been demonstrated to confer superior tensile strength relative to uncompatibilized biocomposites, with additional evidence indicating concurrent enhancements in

tensile strength and elongation at break upon compatibilizer addition [9]. PP-g-MAH also contributed to elevated Young's modulus values in the biocomposite systems under investigation [9]. Furthermore, the inclusion of compatibilizing agents resulted in diminished water absorption characteristics [9]. These compatibilizers augmented the nucleating capability of fillers within the composite structure, with PP-g-MAH demonstrating particular effectiveness in this regard relative to alternative compatibilizer types [7]. Investigation of curaua/polypropylene composite systems revealed that optimal tensile strength was achieved at a MAPP-to-fiber proportion of 6 wt%, identified as the optimum concentration owing to the restricted availability of reactive hydroxyl groups located on the external fiber surface layers [18]. Chemical treatment of PP/PKS biocomposites employing coupling agents has been shown to produce improvements in tensile strength, tensile modulus, flexural strength, flexural modulus, and crystallinity, accompanied by diminished water absorption capabilities [2]. Morphological examinations have confirmed enhanced filler-matrix interaction following chemical modification procedures [2].

Although the advantageous effects of PKS incorporation and MAPP compatibilization have been qualitatively confirmed, the methodical optimization of processing parameters and formulation variables continues to represent a significant research requirement [1]. Prior investigations have generally depended on conventional trial-and-error methodologies to ascertain appropriate filler loadings and particle dimensions [9]. Nevertheless, these approaches may inadequately address the intricate, interactive relationships existing among multiple formulation variables and their collective influence on composite mechanical behavior [6].

Contemporary developments in computational materials science have introduced advanced optimization strategies, incorporating Monte Carlo simulation methodologies, for the systematic engineering and optimization of polymer composites [6]. Monte Carlo approaches, executed through computational algorithms, facilitate the efficient examination of extensive parameter spaces and the identification of optimal combinations that effectively reconcile competing performance requirements [6]. Scholarly work has established that Gaussian process regression in conjunction with Monte Carlo sampling across randomized iterations can successfully represent nonlinear relationships and uncertainty propagation within datasets, surpassing the performance of conventional models including support vector machines, regression trees, and artificial neural networks [6]. These computationally driven methodologies facilitate informed material design and optimization processes, particularly under conditions of limited data availability [6]. Sensitivity analyses have identified filler weight fraction, matrix tensile strength, and surface modification approaches as the predominant factors affecting predictive accuracy [6].

Notwithstanding the expanding body of literature addressing PKS-reinforced PP composites, several knowledge gaps persist within the existing scholarly record [1, 9]. Firstly, although the consequences of filler loading on mechanical properties have been examined, the combined influence of particle size and filler concentration on tensile performance has yet to be comprehensively optimized through advanced computational techniques [6]. Secondly, the particular application of these materials to rigid food packaging encompassing plates, cups, trays, containers, and lids necessitates a customized optimization strategy that effectively reconciles

strength and stiffness requirements to ensure structural integrity during service [17]. Thirdly, the identification of optimal formulation parameters capable of simultaneously maximizing diverse mechanical performance indicators namely strength, stiffness, and their equilibrium has not been methodically addressed [6].

Consequently, the principal aim of this research endeavor is the development and optimization of a rigid biocomposite material formulation possessing enhanced mechanical characteristics, specifically engineered for rigid food service and packaging applications [16]. Palm kernel shell powder (PKSP) undergoes comprehensive characterization, and MAPP-enhanced PP/PKSP composites are fabricated through melt blending followed by compression molding [1]. Tensile strength and tensile stiffness are methodically assessed in accordance with ASTM protocols across a range of PKSP concentrations (5 wt% to 25 wt%) and particle size fractions (75 µm, 250 µm, and 500 µm) [9]. Monte Carlo optimization algorithms, implemented via Python programming scripts, are subsequently applied to numerically ascertain the optimal particle size and loading combinations that yield the most favorable balance of strength and stiffness, maximum overall strength, and maximum overall stiffness [6]. This investigation contributes to the overarching objectives of agricultural waste valorization, advancement of circular economic principles, and development of environmentally preferable polymeric materials for packaging applications [17], thereby addressing the urgent environmental necessity to supplant conventional petroleum-derived plastics with sustainable alternatives [4, 8, 11].

II. MATERIALS AND METHODS

Collection of Materials

Maleic anhydride-grafted polypropylene (MAPP), sourced from Indorama Eleme Petrochemicals Limited (IEPL), Port Harcourt, was dried at 90 °C for 10 hours to remove residual moisture before further processing. Palm kernel shells (PKS), obtained from Aniuzo Oil (Emene Industrial Layout, Enugu), were cleaned, dried, milled, and sieved into 75 µm, 250 µm, and 500 µm fractions. Prior to processing, the sieved PKS (PKSP) underwent partial carbonization at 300 °C to drive off moisture and light volatiles without fully degrading the biomass structure thereby yielding a carbon-rich solid.

Design of Experiments (DOE)

A Python script for Monte Carlo–based Design of Experiments (DOE) was applied to model the tensile strength and stiffness of MAPP-enhanced polypropylene filled with partially oxidized PKSP, considering 3 particle sizes and 5 filler loadings. While the full factorial design comprises 15 experiments, the Monte Carlo optimization can selectively prioritize or augment these combinations.

Mathematical Formulation

A Monte Carlo mathematical formula for polymer composite optimization was used for the design calculation.

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Let the design vector be

$$\mathbf{X} = [x_1, x_2, x_3, \ldots, x_n]$$

where

- x_1 = Particle size (µm)
- x_2 = Filler loading (wt%)
- x_3 = MAPP content (wt%)
- x_4 = Processing temperature (optional)
- x_5 = Screw speed (optional)

Each variable is sampled from a uniform distribution within its experimental limits:

$$x_i \sim U(x_{i,\min}, x_{i,\max})$$

The response is predicted using the quadratic response surface model:

$$\hat{Y} = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 + \sum_{i<j}^{n} \beta_{ij} X_i X_j$$

The Monte Carlo optimization searches for the design vector that maximizes (or minimizes) the objective:

$$\mathbf{X}^* = \arg\max_{\mathbf{X} \in \Omega} \hat{Y}(\mathbf{X})$$

where Ω is the feasible design space defined by the variable bounds.

For multi-response optimization (e.g., maximizing tensile strength, tensile modulus, flexural strength, and impact strength simultaneously), a composite objective such as the geometric mean or desirability function can be used:

$$D = \left(\prod_{i=1}^{m} d_i \right)^{1/m}$$

where d_i is the individual desirability of the i-th response and m is the number of responses. The optimal formulation is obtained by maximizing the overall desirability:

$$\mathbf{X}^* = \arg\max_{\mathbf{X} \in \Omega} D(\mathbf{X})$$

Experimental Design Framework

Table 1: Experimental Design Framework

Factor	Levels	Rationale
PKSP Particle Size	75, 250, 500 µm	Three distinct sizes to evaluate the effect of filler fineness on mechanical properties
Filler Loading	0, 5, 10, 15, 20, 25 wt%	Five loading levels and neat MAPP - enhanced PP (0 wt.%) as a control baseline

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Composite formulation

MAPP-enhanced PP was selected over neat homopolymer PP to promote superior interfacial adhesion with the PKSP filler. This improved binding minimizes voids and interfacial defects, thereby maximizing both the tensile strength and stiffness of the composite. Furthermore, the PKSP was lightly carbonized in a Carbolyte-300 carbonizer to moderately elevate its carbon content which enhances matrix rigidity and stiffness while preserving sufficient O– and OH– groups to ensure strong MAPP-mediated bonding and retain tensile strength. As a result, this partially carbonized filler yields a composite that is significantly stiffer than one containing raw PKSP, yet avoids the strength loss typically associated with fully carbonized PKSP.

Composite plaques were subsequently prepared according to the formulations outlined in Table 2, with PKSP loadings ranging from 0 to 25 wt%.

Table 2: Composite Matrix Formulation

Formulation Code	PKSP Size (μm)	PKSP (wt%)	MAPP-enhanced PP (wt%)
PP-0	0	0	100
S75-L5	75	5	95
S75-L10	75	10	90
S75-L15	75	15	85
S75-L20	75	20	80
S75-L25	75	25	75
S250-L5	250	5	95
S250-L10	250	10	90
S250-L15	250	15	85
S250-L20	250	20	80
S250-L25	250	25	75
S500-L5	500	5	95
S500-L10	500	10	90
S500-L15	500	15	85
S500-L20	500	20	80
S500-L25	500	25	75

Composite fabrication

The fabrication process consisted of the following steps:

1. Drying:

The MAPP-enhanced PP pellets and slightly carbonized PKSP filler were dried at 90°C for 10 hours to removed absorbed moisture, which could otherwise cause voids during measurement and melt processing.

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2. Weighing:
The required amount of MAPP- enhanced PP and slightly carbonized PKSP were accurately weighed using a digital balance with a precision of ± 0.01 g, according to the formulation in Table 3.1. the total batch weight for each formulation was kept constant at 500g to maintain consistent processing conditions.

3. Pre-mixing (Dry Blending):
The weighed MAPP-enhanced PP and the partially carbonized PKSP fillers were initially dry-mixed manually in a high-speed laboratory blender at room temperature for 5 minutes at 1000 rpm. This set ensures a preliminary homogenous distribution of the PKSP particulates within the PP matrix before melt processing according to the specified formulations.

4. Melt compounding:
The mixtures were melt-blended using a twin-screw extruder at a temperature profile of 170-185°C from the speed zone to the die with a screw speed of 60 rpm. The mixture was compounded for 10 minutes to achieve uniform dispersion of the PKSP particles within the molten PP matrix for each composite formulation.

5. Molding:
The different compounded mixtures were placed into a square shaped mold cavity (dimension of 15 mm x 15 mm x 100 mm) that was preheated to 180°C. The compounded mixture was properly pressed inside the mold and was held for 5 minutes to allow the materials to fully fill the mold cavity and eliminate internal voids.

6. Cooling:
The mold was then cooled to room temperature under pressure using a water circulating cooling system for 4 hours at a rate of approximately 10℃/mm to prevent thermal shrinkage and warpage.

7. Demolding:
After cooling, the solidified square composites rods were carefully removed from the mold.

Characterization and Testing.
Tensile properties (strength and stiffness) of the molded composites were evaluated per ASTM standards using an electronic universal testing machine (UTM). A statistical treatment of the experimental data was performed to determine the formulation that achieves the most favorable specific-strength-to-specific-stiffness ratio.

The target criteria were derived from the established property profiles of mineral-filled rigid PP composites utilized in extreme-performance applications, including premium speaker cones subject to Klippel optimization protocols.

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Plate 1: MAPP enhanced Polypropylene



Plate 2: Dried Palm kernel shell



Plate 3: Grinded Palm Kernel Shell Powder



Plate 4: The molded test pieces

III. RESULTS AND DISCUSSION

Characterization of PKSP

Characterization of the PKSP was carried out using Fourier-transform infrared (FTIR) spectroscopy, scanning electron microscopy (SEM), and energy-dispersive X-ray (EDX) spectroscopy. FTIR analysis was performed with an FTIR-530 spectrometer, while SEM imaging was conducted on a TESCAN VEGA 3 LMH instrument.

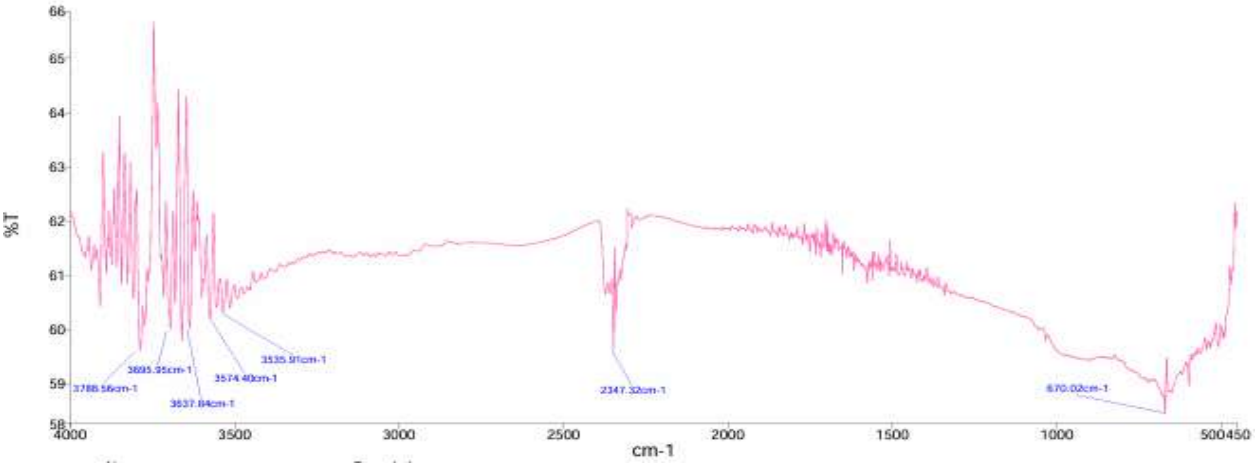


Figure 1: The FTIR of PKSP

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Table 3: PKSP FTIR Major Peaks

Wavenumber (cm^{-1})	Functional Group	Interpretation
3728 cm^{-1}	O–H stretching	Free hydroxyl groups from cellulose, absorbed water, and phenolic compounds
3638 cm^{-1}	O–H stretching	Alcoholic and phenolic hydroxyl groups
3574 cm^{-1}	O–H stretching	Hydrogen-bonded hydroxyl groups in lignin cellulose
3346 cm^{-1}	Broad O–H stretch	Strong indication of cellulose and moisture content
2347 cm^{-1}	CO_2 absorption	Atmospheric carbon dioxide or instrumental artifact
1600–1500 cm^{-1}	Aromatic C=C stretching	Presence of lignin aromatic structures
1450–1370 cm^{-1}	C–H bending	Cellulose and hemicellulose vibrations
1200–1000 cm^{-1}	C–O stretching	Alcohols, ethers, and polysaccharides
670 cm^{-1}	C–H out-of-plane bending	Aromatic compounds and lignin-related structures

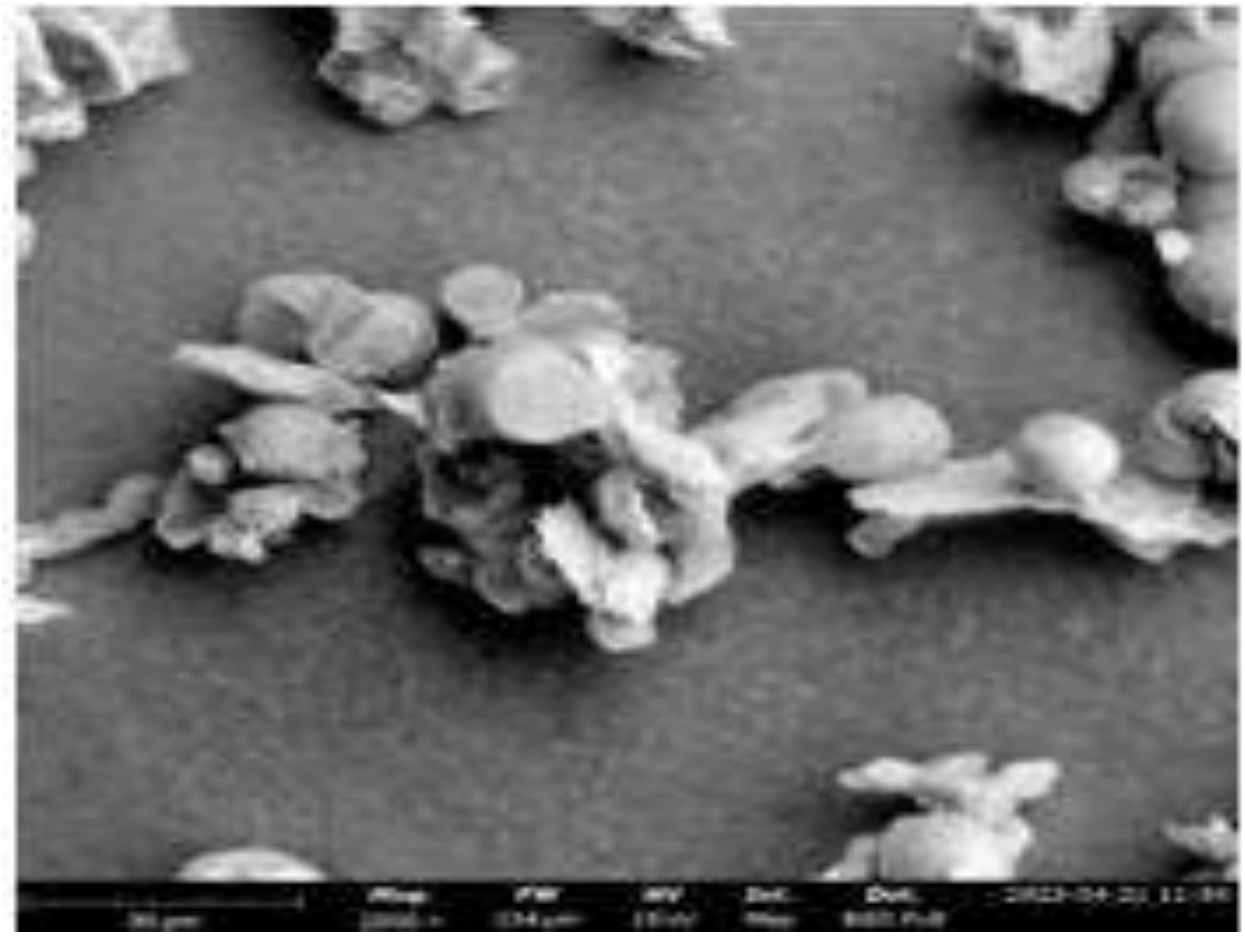


Figure 2: SEM 1000x magnification

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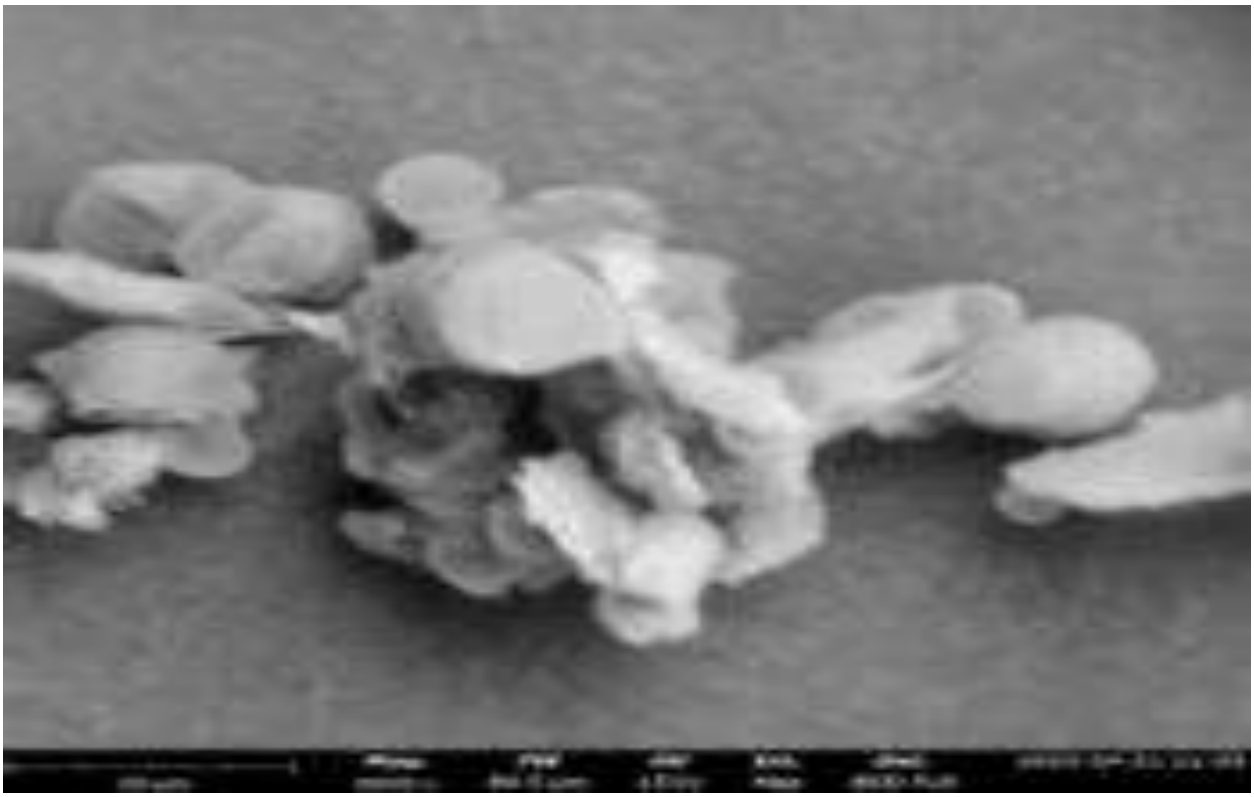


Figure 3: SEM 2000x magnification

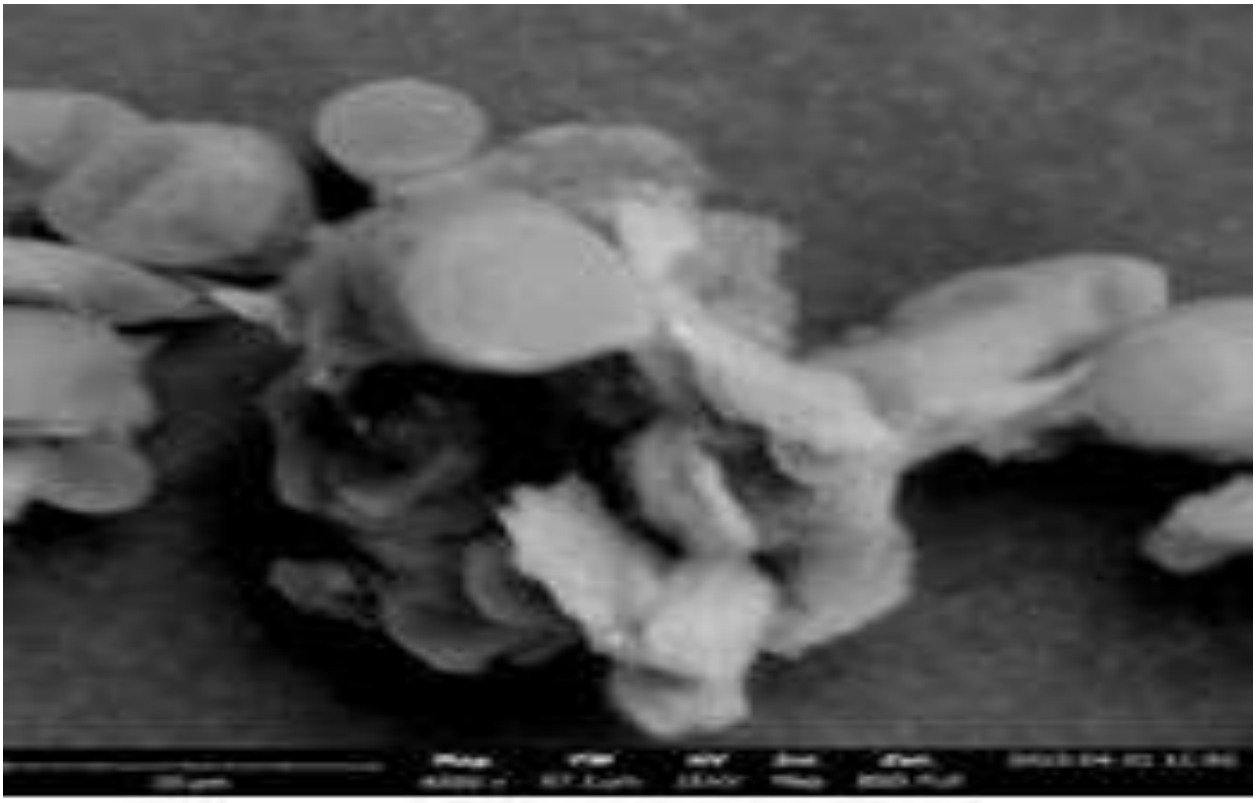


Figure 4: SEM 3000x magnification

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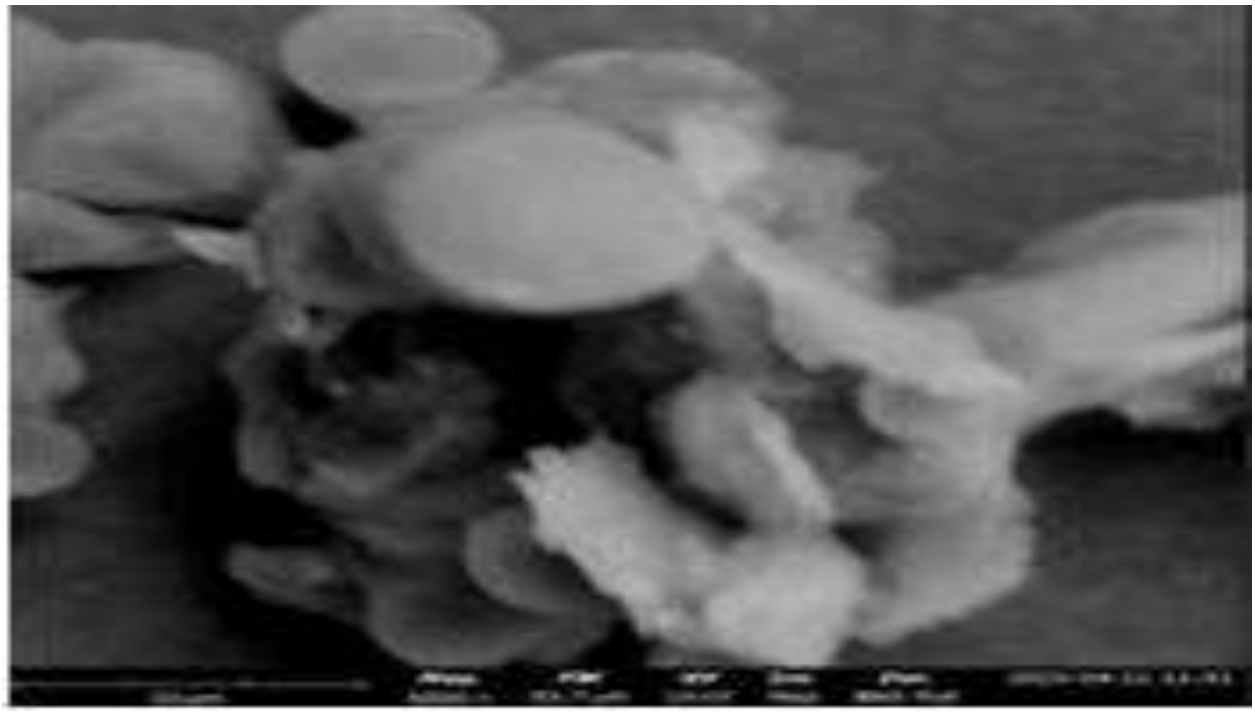
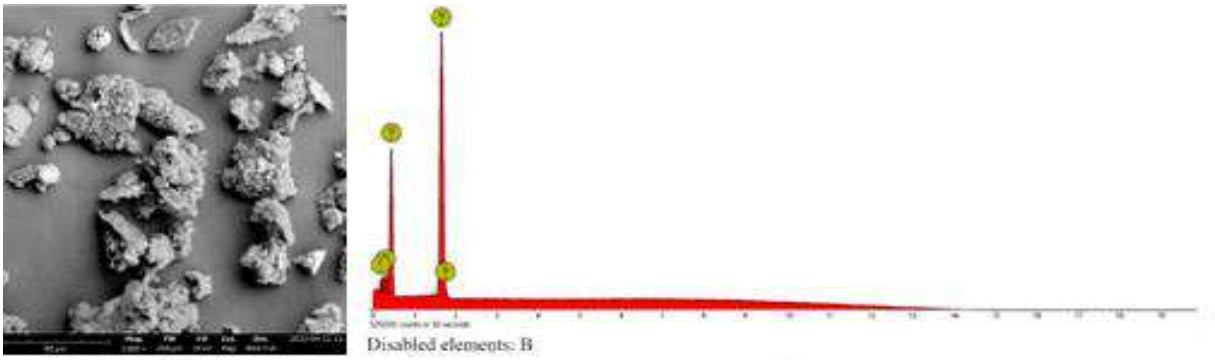
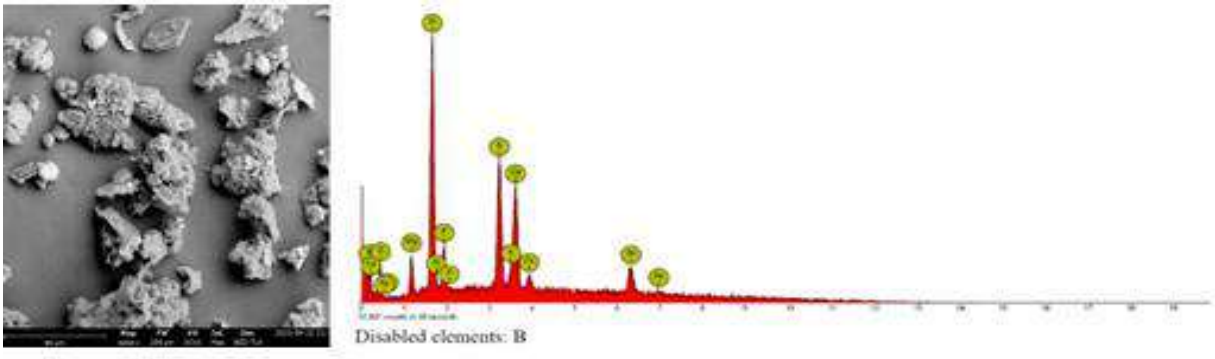


Figure 5: SEM 4000x magnification



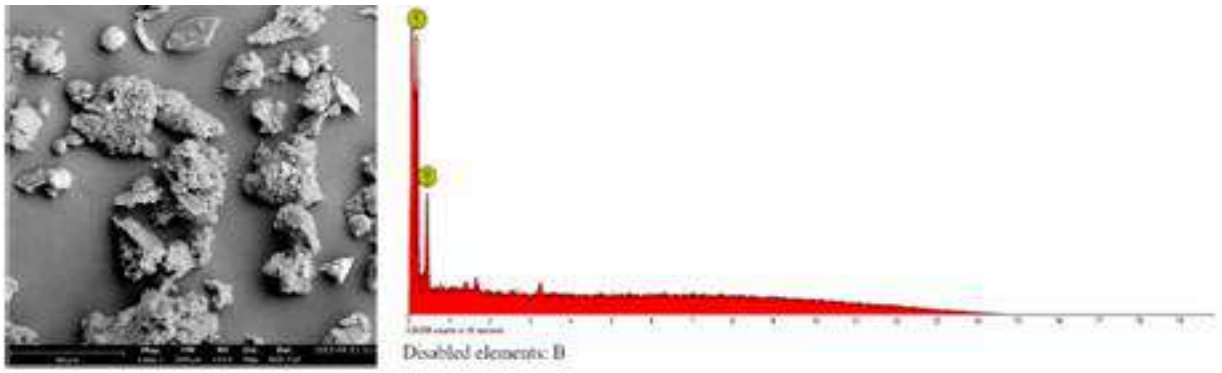
(a) (b)

Fig. 6: (a) Spot 1 EDX; (b) EDX image of the distribution of Spot 1.



(a) (b)

Fig. 7: (a) Spot 2 EDX; (b) EDX image of the distribution of Spot 2.



(a) (b)

Fig. 8: (a) Spot 3 EDX; (b) EDX image of the distribution of Spot 3.

Table 4: EDX Characterization result for sport 1

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
8	O	Oxygen	71.12	63.77
14	Si	Silica	17.56	27.65
7	N	Nitrogen	8.62	6.76
6	C	Carbon	2.66	1.79

Table 5: EDX Characterization result for sport 2

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
8	O	Oxygen	36.28	20.50
14	Si	Silicon	20.05	19.90
19	K	Potassium	14.09	19.47
20	Ca	Calcium	12.52	17.73
12	Mg	Magnesium	6.34	5.44
26	Fe	Iron	5.95	11.76
15	P	Phosphorus	4.70	5.16

Table 6: EDX Characterization result for sport 3

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
8	O	Oxygen	72.33	77.69
6	C	Carbon	27.65	22.29

FTIR analysis of PKSP (Figure 1) revealed seven characteristic peaks (Table 3), indicating the presence of O–H, C–O, C–H, and C=O groups. SEM imaging at four magnifications (Figures 2–5) showed no notable morphological differences at the highest resolution. EDX spot analysis at three locations (Tables 4–6; Figures 6a–b, 7a–b, and 8a–b) revealed variable elemental distributions, though oxygen (O), silicon (Si), and carbon (C) consistently emerged as the predominant elements across all tested spots.

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Table 7: Strengths and stiffnesses for each of wt.% and particle size of PKSP in the matrix.

Sample PKSP Size (µm)	MAPP-enhanced PP (wt%)	PKSP (wt%)	Strength (MPa)	Stiffness (GPa)
75	100	0	33.9	1.64
75	95	5	34.04	2.276
75	90	10	34.18	2.912
75	85	15	34.32	3.548
75	80	20	34.46	4.184
75	75	25	34.6	4.82
250	100	0	33.9	1.64
250	95	5	33.4	2.34
250	90	10	32.9	3.04
250	85	15	32.4	3.74
250	80	20	31.9	4.44
250	75	25	31.4	5.14
500	100	0	33.9	1.64
500	95	5	33.15	2.44
500	90	10	32.4	3.24
500	85	15	31.65	4.04
500	80	20	30.9	4.84
500	75	25	30.15	5.64

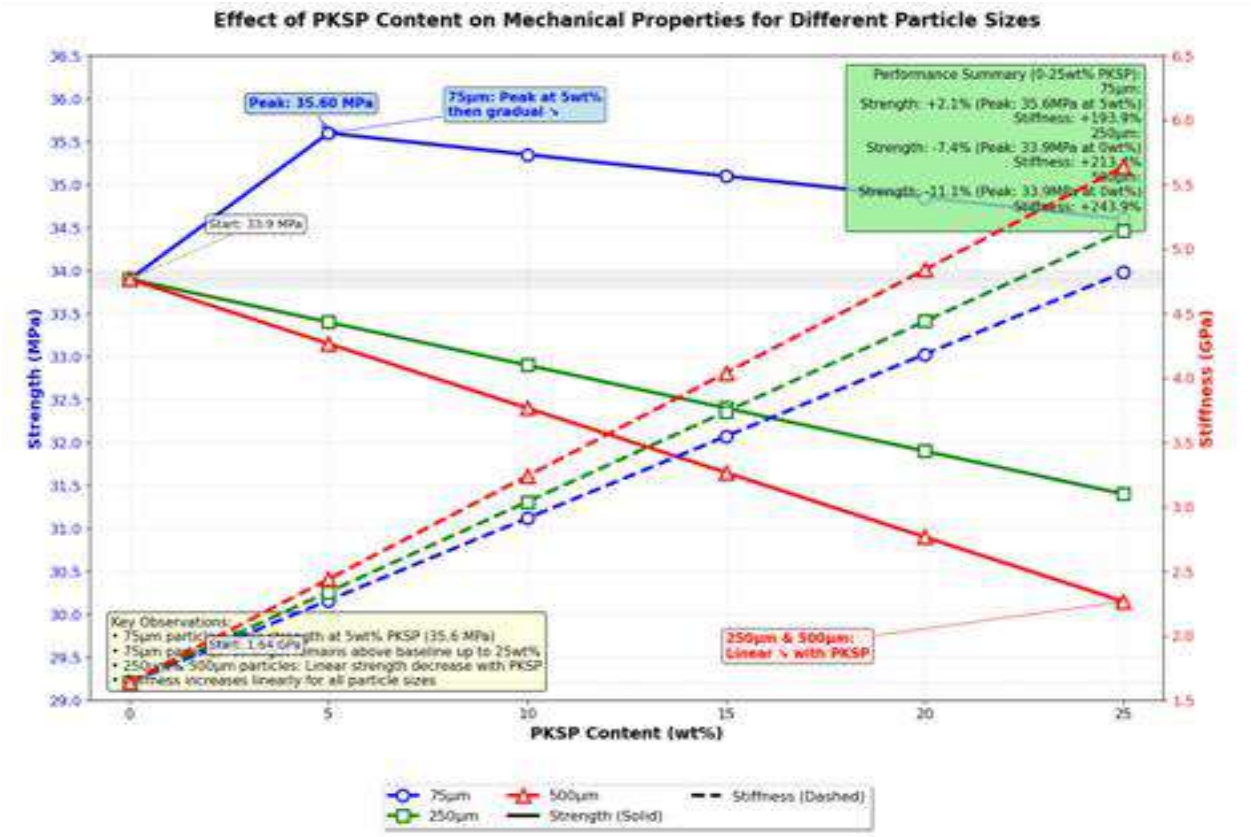


Figure 9: showing the plots of strength (MPa) and stiffness (GPa) versus PKSP content (wt.%)

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The graph illustrates the mechanical properties of composites as a function of PKSP content (0–25 wt.%) for three particle sizes: 75 µm (blue), 250 µm (green), and 500 µm (red). Strength values (left y-axis) range from 34.0 to 35.60 MPa, while stiffness values (right y-axis) range from 1.5 to 6.5 GPa.

Optimization results

Several different optimizations relying heavily on the Monte-Carlo basis were performed on the results and chart shown above. These include weighted, Pareto, product, geometric mean and desirability function optimizations.

The results of the optimizations are displayed below:

```
================================================================================
COMPREHENSIVE OPTIMIZATION ANALYSIS FOR PKSP COMPOSITES
================================================================================

1. WEIGHTED OPTIMIZATION (Equal weights for Strength & Stiffness):
--------------------------------------------------------------------------------
Size:  75µm, PKSP: 25wt% | Strength: 34.60 MPa, Stiffness: 4.820 GPa | Score: 0.806
Size: 250µm, PKSP: 25wt% | Strength: 31.40 MPa, Stiffness: 5.140 GPa | Score: 0.552
Size: 500µm, PKSP: 25wt% | Strength: 30.15 MPa, Stiffness: 5.640 GPa | Score: 0.500

2. PARETO OPTIMAL SOLUTIONS (Non-dominated points):
--------------------------------------------------------------------------------
 1. Size:  75µm, PKSP:  5wt% | Strength: 35.60 MPa, Stiffness: 2.276 GPa
 2. Size:  75µm, PKSP: 10wt% | Strength: 35.35 MPa, Stiffness: 2.912 GPa
 3. Size:  75µm, PKSP: 15wt% | Strength: 35.10 MPa, Stiffness: 3.548 GPa
 4. Size:  75µm, PKSP: 20wt% | Strength: 34.85 MPa, Stiffness: 4.184 GPa
 5. Size:  75µm, PKSP: 25wt% | Strength: 34.60 MPa, Stiffness: 4.820 GPa
 6. Size: 250µm, PKSP: 25wt% | Strength: 31.40 MPa, Stiffness: 5.140 GPa
 7. Size: 500µm, PKSP: 25wt% | Strength: 30.15 MPa, Stiffness: 5.640 GPa

3. PRODUCT OPTIMIZATION (Maximize Strength × Stiffness):
--------------------------------------------------------------------------------
Size:  75µm, PKSP: 25wt% | Strength: 34.60 MPa, Stiffness: 4.820 GPa | Product: 166.77 MPa·GPa
Size: 250µm, PKSP: 25wt% | Strength: 31.40 MPa, Stiffness: 5.140 GPa | Product: 161.40 MPa·GPa
Size: 500µm, PKSP: 25wt% | Strength: 30.15 MPa, Stiffness: 5.640 GPa | Product: 170.05 MPa·GPa

4. GEOMETRIC MEAN OPTIMIZATION:
--------------------------------------------------------------------------------
Size:  75µm, PKSP: 25wt% | Strength: 34.60 MPa, Stiffness: 4.820 GPa | Geometric Mean: 0.806
Size: 250µm, PKSP: 20wt% | Strength: 31.90 MPa, Stiffness: 4.440 GPa | Geometric Mean: 0.474
Size: 500µm, PKSP: 10wt% | Strength: 32.40 MPa, Stiffness: 3.240 GPa | Geometric Mean: 0.406

5. DESIRABILITY FUNCTION OPTIMIZATION:
--------------------------------------------------------------------------------
Size:  75µm, PKSP: 25wt% | Strength: 34.60 MPa, Stiffness: 4.820 GPa | Desirability: 0.911
Size: 250µm, PKSP: 25wt% | Strength: 31.40 MPa, Stiffness: 5.140 GPa | Desirability: 0.897
Size: 500µm, PKSP: 25wt% | Strength: 30.15 MPa, Stiffness: 5.640 GPa | Desirability: 0.920
```

Figure 10: showing the results of Monte-Carlo based optimizations for the experimental results

```
============================================================
==========
3D DESIRABILITY INTERACTION PLOT FOR PKSP COMPOSITE
OPTIMIZATION
============================================================
==========
Total data points: 18
Size range: 75.0 - 500.0 µm
PKSP range: 0.0 - 25.0 wt%
Strength range: 30.42 - 35.65 MPa
Stiffness range: 1.589 - 5.504 GPa

Response Surface Models:
Strength Model R²: 0.9309
Stiffness Model R²: 0.9963

Strength Model Coefficients:
  Size: -0.0177
  PKSP: 0.0628

Stiffness Model Coefficients:
  PKSP: 0.1310
```

Figure 11a: 3D Desirable interaction plot for PKSP Composite Optimization

```
============================================================
==========
GENERATING 3D DESIRABILITY INTERACTION PLOTS
============================================================
==========

Processing: Equal Importance (50/50)
  Optimal Point - Size: 50.0 µm, PKSP: 25.0%, Desirability:
0.8759
  Predicted - Strength: 35.46 MPa, Stiffness: 4.704 GPa

Processing: Strength-Focused (75/25)
  Optimal Point - Size: 50.0 µm, PKSP: 25.0%, Desirability:
0.9190
  Predicted - Strength: 35.46 MPa, Stiffness: 4.704 GPa

Processing: Stiffness-Focused (25/75)
  Optimal Point - Size: 50.0 µm, PKSP: 25.0%, Desirability:
0.8349
  Predicted - Strength: 35.46 MPa, Stiffness: 4.704 GPa

Processing: Strength-Dominant (90/10)
  Optimal Point - Size: 50.0 µm, PKSP: 21.5%, Desirability:
0.9506
  Predicted - Strength: 35.58 MPa, Stiffness: 4.276 GPa

Processing: Stiffness-Dominant (10/90)
  Optimal Point - Size: 132.5 µm, PKSP: 25.0%, Desirability:
0.8196
  Predicted - Strength: 33.64 MPa, Stiffness: 4.901 GPa
```

Figure 11b: 3D Desirable interaction Plot continues

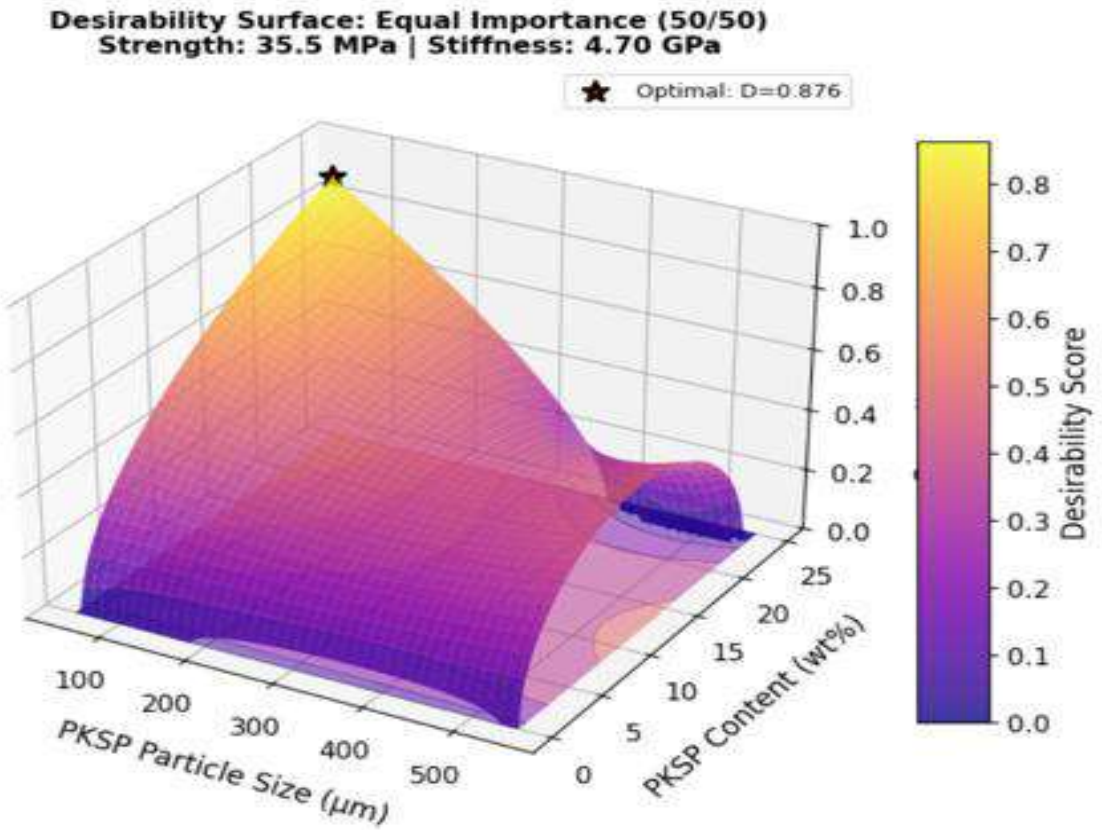


Figure 4.15.1: 3D Desirability surface Plot for [Strength and Stiffness (50/50)]

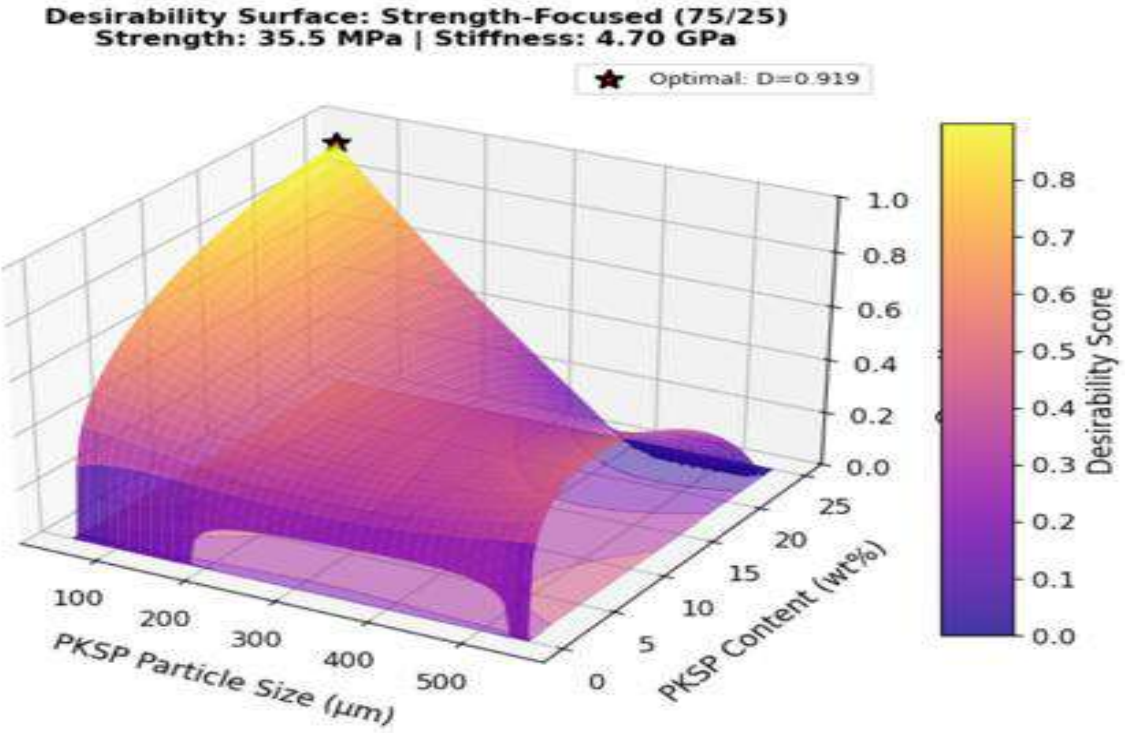


Figure 4.15.2: 3D Desirability Surface Plot [Strength Focus (75/25)]

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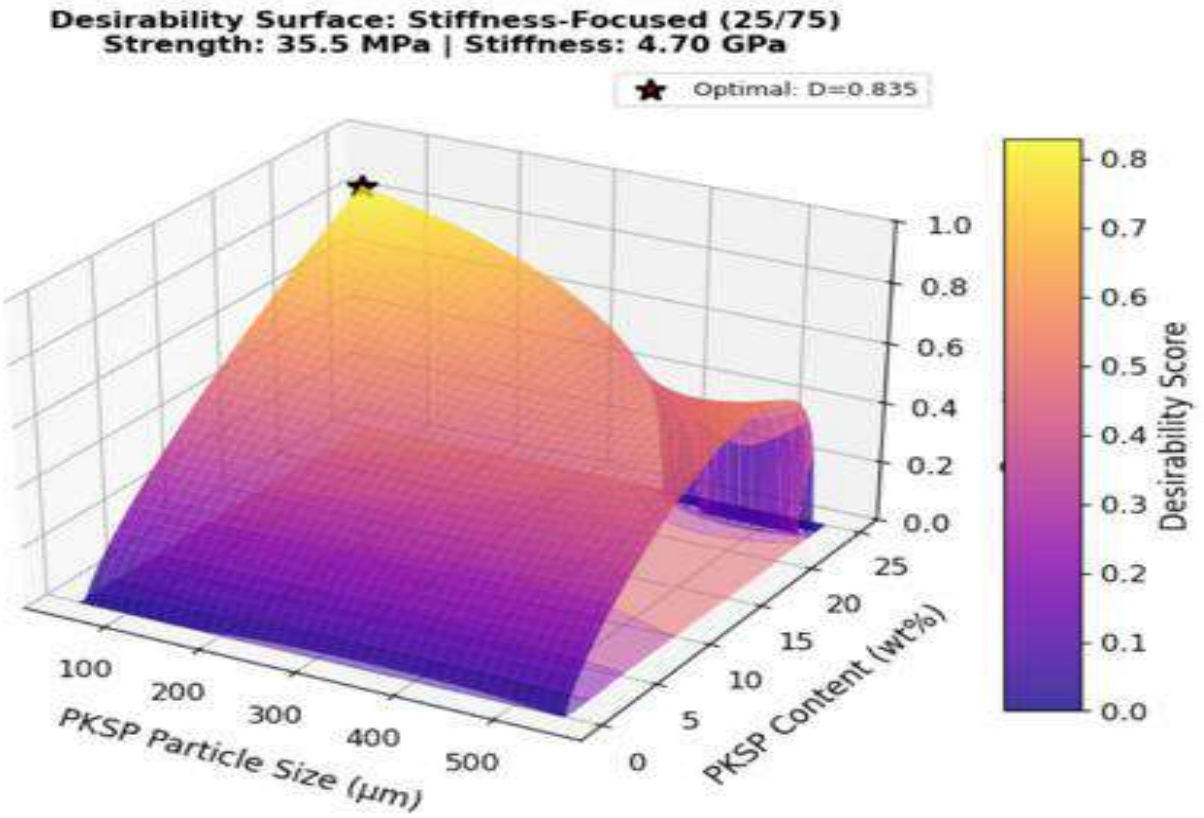


Figure 4.15.3: 3D Desirability Surface Plot [Stiffness-focused (25/75)

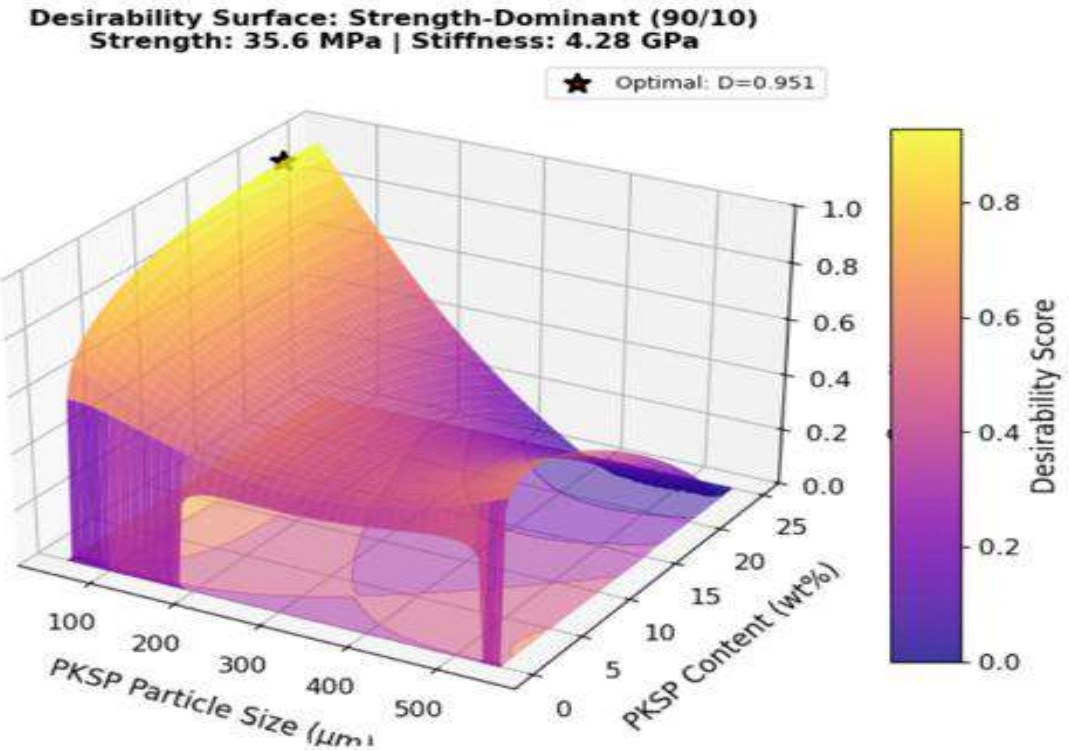


Figure 4.15.4: 3D Desirability surface Plot [Strength- Dominant (90/10)]

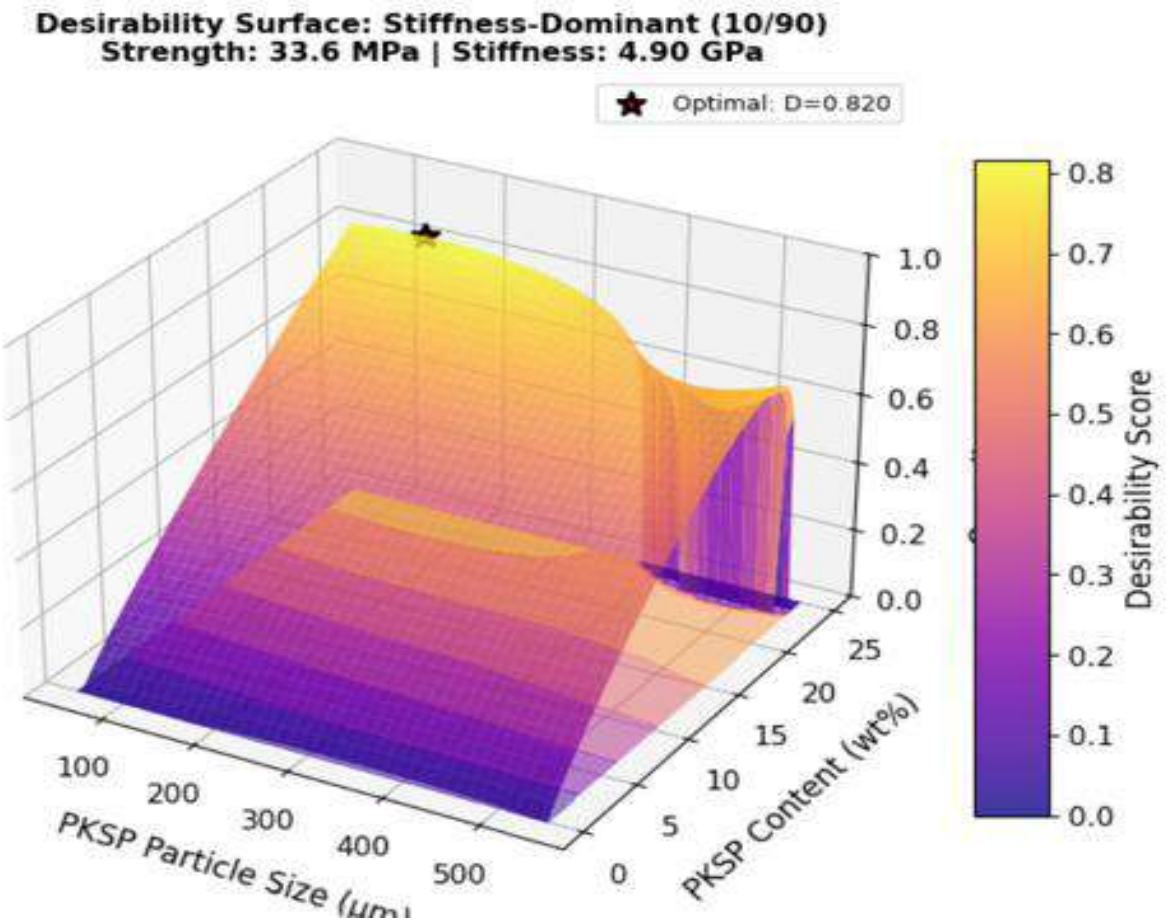


Figure 4.15.5: 3D Desirability surface Plot [Stiffness-Dominant (10/90)]

Key Observations Discussion

Figure 1 presents the tensile strength (left y-axis, 29–36.5 MPa) and stiffness (right y-axis, 1.5–6.5 GPa) of the MAPP-enhanced PP/PKSP composites as a function of filler content (x-axis, 0–25 wt%) for particle sizes of 75 µm (blue), 250 µm (green), and 500 µm (red).

Broadly, the results show that while stiffness increases with PKSP loading across all particle sizes, the strength response is strongly size-dependent. For the finest 75 µm particles, both strength and stiffness rise relative to the neat polymer by 2.1 % and 193.9 %, respectively attributable to effective stress transfer from the matrix to the well-dispersed filler. In contrast, for the 250 µm and 500 µm fractions, increasing filler content leads to a progressive reduction in tensile strength, although stiffness continues to improve.

A closer examination highlights the distinct behavior of the 75 µm filler: strength peaks at 5 wt% loading (35.6 MPa), and even at the maximum 25 wt% loading, it remains above the unfilled matrix baseline (34.6 MPa vs. 33.9 MPa), indicating robust interfacial bonding. The larger particle sizes, however, exhibit an approximately linear decline in strength, with the 500 µm grade showing the most pronounced degradation. Regarding stiffness, all formulations display a monotonic, near-linear increase with PKSP content; the greatest enhancement (+244 %) is observed for the 500 µm particles at 25 wt%.

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From an optimization perspective, the highest tensile strength is achieved with 75 µm particles at 5 wt% PKSP (35.6 MPa), whereas maximum stiffness is obtained with 500 µm particles at 25 wt% PKSP (5.64 GPa). For a balanced performance profile, the 75 µm particles within the 5–10 wt% range are recommended a conclusion further supported by the strength × stiffness performance index, which identifies the 75 µm / 5 wt% formulation as offering the best overall combined properties. The figure is clearly annotated to delineate these critical trends.

Weighted optimisation, visual observation

Visual inspection of the 3 intersection points of the 3 sets of blue, green and red solid and broken lines in Figure 1 leads to the following observation/conclusion:

a.) The 3 intersection points corresponding to the blue (75µm), green (250µm) and red (500µm) sets of lines are (34.5MPa, 5.2GPa, 28wt%), (32.4MPa, 3.75GPa, 15wt%) and (32.2MPa, 3.6GPa, 12wt%) respectively. These are the 3 intersection points where the values of strength and stiffness are weightedly balanced for each of the 3 PKSP sizes 75, 250 and 500µm respectively.

Monte-Carlo optimisation

Monte Carlo optimization, implemented via a Python interface, was applied to identify the optimal MAPP-reinforced PP/PKSP composite formulation. Weighted, Pareto, product, geometric mean, and desirability function analyses all consistently converged on the (75 µm, 25 wt%) combination as the preferred candidate. The geometric mean approach particularly favored this set due to its lowest variation in both strength and stiffness across increasing filler content, while the desirability function ranked it closely behind the (500 µm, 25 wt%) formulation.

The selection of (75 µm, 25 wt%) is attributed to its ability to maximize stiffness with only a marginal trade-off in strength a critical advantage when using lightly carbonized, optimally treated PKSP filler in compression-molded composites. Based on the final optimization report, this formulation is expected to deliver tensile properties of approximately 34.6 MPa (strength) and 4.82 GPa (stiffness). For application-specific needs, two alternative candidates are recommended: (500 µm, 25 wt%) for scenarios where absolute maximum stiffness is the overriding priority, and (75 µm, 5 wt%) for cases requiring the highest attainable tensile strength.

IV. CONCLUSION

Based on comparative tensile data acquired via a programmable electronic universal testing machine (UTM) and subsequent Python-assisted optimization, the following conclusions are drawn. Lightly carbonized palm kernel shell powder (PKSP) effectively reinforces maleic anhydride-grafted polypropylene (MAPP)-enhanced PP matrices. A 25 wt.% PKSP loading gives the highest weighted optimization scores across all particle sizes, with the 75 µm formulation ranked first, thereby representing the optimal strength–stiffness compromise for this composite system. Overall, this study demonstrates that optimally formulated MAPP-enhanced PP/PKSP composites, derived from agricultural waste, offer a promising sustainable alternative for rigid food packaging, supporting waste reduction and circular economy objectives.

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Impact Of Artificial Intelligence in Banking Sector

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***Abstract*—Artificial intelligence is known as "machine intelligence" is intelligence demonstrated by machine that differ from human intelligence, AI is term that is frequently used to characterize robots that are also associated with brain such" learning and problem solving". Artificial intelligence in banking, enhance applications and it has ability to analyse data across multiple variables, fraud detection, customer relationship and many more. Artificial intelligence is the banking as it brings the power of advanced data analytics to combat fraudulent transactions and improve compliance.AI algorithm accomplishes anti money laundering activities in few seconds, otherwise take hours and days. AI also enables banks to manage huge volume of data at record speed to derive valuable insights from it. Features such as AI bots, Digital payment advisers and biometric fraud detection mechanism lead to higher quality of services to a wider customer base. All this translate to increased revenue, reduced cost and boost in profits. The future of artificial intelligence in banking and finance is promising yet plagued with uncertainties, despite the concerns, it is obvious that AI will play a more vital role in the sector, affecting the way users interact and maintain their financial stability AI system offer, anticipate execute personalized financial advice to customer, as well as acquire information on financial strategies lending rate and future market progress.**

***Index Terms*—Concept, Areas, Impact**

I. INTRODUCTION

Artificial Intelligence is typically defined as the ability of a machine to perform cognitive functions we associate withhuman minds, such as perceiving, reasoning, learning, interacting with the environment, problem solving, and even exercising creativity. However, Artificial Intelligence (AI) is actually a combination of advanced computational technologies in varying degrees of maturity. Some of these technologies have been around for decades while others are relatively

new. Itis however an incremental technological evolution, sometimes based on old technologies, which has now been made possible by access to large volumes of data and new capacities in processing these volumes of data. The wording "Artificial Intelligence" is based on terms that can sometimes seem overused as it is used generically to cover multiple technologies. Most of the time, the use of algorithms is limited to mimicking scenarios; reproducing and automating the processing of repetitive tasks that a human being could perform. By AI itis generally "cognitive technologies that rely on large volumes of structured or unstructured data (big data)" that is meant. In this sense, "cognitive intelligence" is defined as any unstructured data processing, modelling that emulates and/or allows to augment and enhance the cognitive abilities of humans. For example, here is a non-exhaustive list of some areas of technological research:
Studying Artificial Intelligence (AI) in the banking sector is essential because it is a primary driver of industry innovation Researching this field helps financial institutions significantly reduce operational costs, automate risk and compliance management, and improve how banks and financial regulators detect fraud in real time.

a. Natural language processing:
Understands language by attributing meaning and purpose. It is often associated with Automatic Speech Recognition and Text to Speech.

b. Cognitive computing:
Support in the realization of cognitive tasks and decision making. These are interactive, iterative and evidence-based systems.

c. Smart analytics/ processing:
Predictive analysis and simulations. These provide support for rule-based automatic actions (e.g., recommendation engines).

d. Deep learning and reinforcement learning:
Structure that moves the focus of machine learning from pattern recognition to a process of sequential and experience-driven decision making.

Major Areas of Artificial Intelligence can be used in banking Sector

Personalized Financial Services	Smart Wallets
Voice Assisted Banking	Customer support
Digitalization instead of branch lines	Reduce Costs

II. REASONS FOR ADOPTION OF AI IN THE BANKING SECTOR

Enhanced Customer Experience:
AI-powered chat bots and virtual assistants can provide personalized customer support, address inquiries, and offer 24/7 assistance. These systems can handle routine tasks, such as balance

inquiries, transaction history, and account management, allowing customers to access information quickly and conveniently.

Fraud Detection and Prevention:
AI algorithms can analyse large volumes of transactional data in real time, identifying patterns and anomalies that may indicate fraudulent activity. This helps banks detect and prevent fraud more effectively, protecting customers and minimizing financial losses.

Risk Assessment and Credit Scoring:
AI algorithms can analyze vast amounts of customer data, including financial history, credit scores, and online behavior, to assess creditworthiness accurately. This enables banks to make moreinformed decisions when granting loans or evaluating risk, leading to better credit management and reduced default rates.

Process Automation:
AI technologies can automate manual and repetitive tasks within banking operations, such as data entry, document processing, and compliance checks. This improves efficiency, reduces costs, and frees up human employees to focus on more complexand strategic activities.

Personalized Financial Recommendations:
By leveraging AI algorithms, banks can analyze customer data to offer tailored financial advice and product recommendations. This can include investment opportunities, personalized savings plans, or loan options that match specific customer needs, leading to improved customer satisfaction and engagement.

Advanced Data Analytics:
AI can analyze vast amounts of structured and unstructured data, extracting valuable insights and identifying market trends. Banks can leverage this informationto make data-driven decisions, refine business strategies, and develop innovative financial products and services.

Regulatory Compliance:
AI technologies can assist banks in monitoring transactions, detecting money laundering activities, and ensuring compliance with regulatory frameworks. AI-powered systems can continuously analyze transactions and flag any suspicious activities, helping banks meet their legal obligations and reducing the risk of non- compliance.

Operational Efficiency:
AI can optimize back-office processes, automate workflows, and improve operational efficiency across various banking functions. By streamlining processes, reducing errors, and increasing productivity, banks can achieve cost savings and provide fasterand more reliable services to customers. It is important to note that while AI brings numerous benefits to the banking sector,

ensuring data privacy, security, and ethical use of AI remains crucial. Banks must prioritize safeguarding customer information and implementing transparent and accountable AI systems.

Key Benefits of Artificial Intelligence (AI) For the Banking Sector

Benefit of AI in Banking Sector						
Early Fraud Detection and Prevention	Credit Scoring and Loan approval	Improved Customer satisfaction	Reduce Cost	Enhancing operational efficiency	Efficient Risk Management	Increase in Revenue

III. LITERATURE REVIEW

(Hickam Sadok, 2022) This article explores the effects of artificial intelligence (AI) use on banks and other financial organisations' credit score assessment processes. These restrictions serve as thefoundation for a new age of economic law that introduces the certification of AI algorithms andbank-used data.

(Chandrima Bhattacharya, 2022) Through this paper we understood that literature evaluation andtheoretical studies is completed for diverse worldwide and Indian banks with admire to thecombination of AI to enhance client interactions and inner banking processes. Chatbot use-instances on banking systems are ranked primarily based totally on client experience. Practical/Theoretical implications: Based at the entire image of AI integration with banking operations, evolving Indian banks should recognition at the maximum famous use-instances todraw customers. The correlation among Chatbot use-instances can also additionally gain theinstalled Indian banks to similarly amplify business.

(Ankur Aggarwal, 2022) Explained that once all the banking offerings had been revolving across thesalaried or earners, it emerge as a crucial part of our life. Present look is primarily based upon thescope of synthetic intelligence in client revel in and robot technique automation in banking zone inIndia. Most of the client revel in associated factors confirmed right correlation with AI primarilybased total offerings through banks.

(Saloni Tripathi, 2022) Points out the dynamics of AI platforms in the banking industry and howthey are becoming a significant disruptor. Banks are facing challenges from current technology thatuses intelligent algorithms to replace human labour. Companies must integrate AI into their business strategies and practices to stay competitive.

(Omar H. Fares, 2022) The findings show how three important study areas Strategy, Process, and Customer—are covered by the literature on AI and banking. A systematic consumer credit solution application blueprint (Service Blueprint) that details the customer journey, front stage, backstage, and support procedure in banks was also stated by him in his study paper.

According to Garcia et al. (2023), AI can help mitigate information asymmetries and ethical concerns in the banking industry.
This capability is attributed to features such as transparency, precise dissemination of information, un-changeability, and computational reasoning, facilitated by technologies like smart contracts and automation.

OBJECTIVES OF THE STUDY

1. To understand the concept of Artificial Intelligence in Banking Sector.
2. To study the reason for adoption of AI in banking sector.
3. To study the impact of AI in banking sector.

IV. RESEARCH METHODOLOGY

The topic for the research study is the rise Impact of artificial intelligence in banking sector and the nature of study is theoretical and descriptive. The sources of data collection are both primary and secondary based. Primary data has been collected by conducting an interview. Open ended questions were asked by banking experts to analyze the impact of artificial intelligence on the banking sector.
The other form of source for data collection has been secondary based. The data and the information have been extracted from authenticated websites, books, journals, articles, business magazine and brochure. Through the secondary data, researcher has analyzed the different applications of artificial intelligence in the banking sector and how AI is helping banks to improve their results.

V. SAMPLING PROCEDURE

A convenience sampling technique will be followed to select the respondents for the present study. The study involves on kind of respondent. i.e., customers. Samples of 150 respondents each will draw conveniently form the population of customers. For the purpose of the study Shikaripura town as taken.

VI. RESEARCH DESIGN

Research Type: Descriptive in nature
Research Design: Qualitative
Data Collection: Banking Employees and Customers
Primary Data: through questionnaire
Secondary Data: Through journals, articles and many books.
Tools used: Percentages Analysis.

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VII. SCOPE OF STUDY

The scope of study is to analyze the different applications of AI in banks and in what ways AI could help the banks to improve their performance.

Table No1: - Shows the consumer's perceptions about Artificial Intelligence in Banking and Financial Services which are determine most of the respondents strongly agree with Artificial Intelligence applications user friendly.

Table-1: Shows the familiar with AI technology in banking.

How familiar with AI technology in banking system?	Not familiar at all	Slightly familiar	Moderately familiar	Very familiar	Total
Respondent	35	48	52	15	150
Percentages	23.33	32	34.67	10	100

Source: Primary data

The table no 1 shows that familiar with AI technology using in banking sector. Among them 34.67% of respondent were moderately familiar while 10% are very familiar.

Table-2: Shows the areas of banking operations which AI is most impactful.

Which areas of banking operations do you think AI is most impactful?	Customer Service	Fraud Detection	Loan approval	Risk Management	Investment Advisory	Total
Respondents	65	20	35	22	8	150
Percentage	43.33	13.33	23.33	14.66	5.33	100

Source: Primary data

The table no 2 shows that impact of areas of AI in banking operation. It shows that 43.33% of respondents are agree customer service, 13.33% are Fraud detection 23.33% are Loan approval, 14.66 are Risk Management and 5.33% are Investment advisory.

Table-3: Shows the replace of human involvement in Banking services

Is AI able to successfully replace human involvement in Banking services, in your opinion?	Yes	No	Total
Respondents	90	60	450
Percentage	60	40	100

Interpretation: Most of the respondents AI able to successfully replace human involvement in banking services with 60%.

Table No. 4 Different AI Tool supportive to Customers

AI Tools	Supportive		Not Supportive		Total
	Respondents	Percentage	Respondents	Percentage	
Chat Box	136	90.66	14	9.34	150
IVA	125	83.33	25	16.67	150

Mobile app assistance	140	93.33	10	6.67	150
Fraud detection	145	96.66	5	3.34	150
Credit scoring Model	146	97.33	4	2.67	150
Personalized Financial Advice	132	90	18	10	150
Customer Relationship Management	147	98	3	2	150

Source: Primary data

All the different AI tools quickly accepted and well adopted by the client with proper utility. Customer Relationship Management application with highest rating with 98% supportive highest among all the AI tools. Secondly top rated with Fraud Detection and support in Credit Score adviseswith 97.33% supporting. Need to be more interactive with voice assistance (IVA) with 83.33% as Indian diverse with different language dependence.

Table-6: Shows the factors that customers influence in banking services In Ranking Method

Banking services	Mean	Rank
Credit card services	2.62	6
Online banking	3.26	4
Loans	3.16	5
Money transfers	4.56	2
ATM withdrawals	5.06	1
Mobile banking	4.50	3
Investment services	2.55	7
Others	1.29	8

Interpretation: The banking services that influences customers utilized the most of ATM withdrawals has ranked 1.

Impact of Artificial Intelligence in Banking:

Banks use artificial intelligence (AI) to provide, predict and execute personalized financial advice to customers and get quick information about financial strategies, loan rates and future markets.

The impact of artificial intelligence on the banking industry is as follows: -

Customer satisfaction:

Artificial intelligence allows banks to improve revenue, decision making andcustomer relationship management, as well as providing customized and efficient services that aregood for customers.

Chatbot:

Bot is the meaning of Robot. Chatbot is a chatbot that can be used to perform tasks or followa predefined process. Chatbots are a type of artificial intelligence that can be used in financial institute ions. A chatbot is available 24 hours a day, 7 days a week and can provide excellent customer service.

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Personal financial guidance:
Artificial intelligence helps customers make easy, fast financial decisions using the latest information on br> Provide recommendations on current market trends and stocks and bonds people can invest in.

Digital Wallet:
Digital wallet allows users to use digital currency to buy anything online through their mobile phone or computer.
Interactive Voice Response System (IVRS): A voice that works with customers, answering specific q questions, directing them to financial institutions, and providing a good customer experience.

Crime Detection:
Artificial intelligence detects financial fraud by scanning large amounts of transaction on data and monitoring for unusual or activity patterns. Artificial intelligence can reduce financial fraud, speed up processes, prevent security breaches, and facilitate machine learning.

Improve customer service:
Customer satisfaction has an impact on the performance of the banking industry and makes people think about the banking industry. Products of financial institutions. It alsohas an impact on banks' objectives and insurance policies.

Better regulatory compliance:
Intelligence applications often rely on fraud metrics to track customers, analyze transactions, identify suspicious behavior, and measure the difficulty of complying with different rules. Artificial intelligence provides significant benefits to customers through personalization, reducing risks and costs, increasing employee productivity and enabling improvements.

Risk Management:
Risk management should reduce fraud by instantly analyzing transactions for suspicious patterns and assessing customer behavior. To provide suggestions to creditworthiness and risk assessors to reduce risk.

Portfolio Management:
Artificial intelligence systems and machine learning technologies create personalized portfolios based on customers' resource constraints, behaviors and preferences. Financial markets and artificial intelligence are about to usher in the next wave of the digital revolution. Therefore, artificial intelligence has changed many areas of the banking system, making money transfers safer and more efficient.

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VIII. FINDINGS

1. Majority of respondents likely to use AI technology in banking system with 34.67%
2. Majority of respondents likely to use the areas of banking operations which AI is most impactful with 43.33%
3. Most of the respondents AI able to successfully replace human involvement in banking services with 60%
4. External communication the banking services that influence customers utilized the most of ATM withdrawals has ranked 1

IX. SUGGESTION

AI can be used in banking to automate customer service through chat bots, enhance fraud detection using machine learning, personalize financial offerings based on customer data, optimize loan approvals with predictive algorithms, streamline compliance processes with AI-driven regulatory technology, improve risk management by analyzing financial data in real-time, enhance cyber security through advanced threat detection systems, enable smarter investment strategies with AI-driven market analysis, improve operational efficiency through robotic process automation (RPA), and provide customers with tailored financial advice using AI-powered virtual assistants.

X. CONCLUSION:

The impact of AI in the banking sector can be observed in almost every aspect of financial institutions' operations. From reducing costs, automatic document processing and boosting profits to strengthening security, supporting decision-making, and delivering tailored customer experiences – artificial intelligence already helps with all of that. Therefore, we recommend that you implement AI as soon as possible.

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Advancing Sustainable Development Goals Through Humanitarian WASH Interventions: Evidence, Gaps, And A Transformative Agenda for Water, Sanitation, And Hygiene in Crisis Settings

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Abstract*—Access to water, sanitation, and hygiene remains among the most acutely unmet needs in humanitarian crises globally, yet the relationship between humanitarian WASH interventions and Sustainable Development Goal achievement has been treated in both policy discourse and academic literature as incidental to the primary emergency mandate rather than as a strategic priority. This article addresses that gap through a systematic narrative review of 87 peer-reviewed studies, intergovernmental reports, NGO programme evaluations, and framework documents published between 2020 and 2025, synthesising evidence on how humanitarian WASH interventions contribute to, constrain, or create pathways toward SDG achievement across health (SDG 3), education (SDG 4), gender equality (SDG 5), equitable access (SDG 10), climate action (SDG 13), and governance (SDG 16). Four analytical arguments organise the synthesis. First, humanitarian WASH constitutes a structural SDG investment whose returns extend across multiple goal dimensions when designed with deliberate SDG alignment. Second, the humanitarian-development nexus remains the central governance gap preventing WASH interventions from generating durable SDG progress beyond the immediate crisis period. Third, climate change is fundamentally reshaping the scale, character, and SDG implications of humanitarian WASH need in ways that existing SDG monitoring frameworks do not yet adequately reflect. Fourth, localization, focusing community knowledge, local actors, and context-adaptive governance, represents the most consequential systemic change available for improving both WASH quality and SDG alignment in humanitarian settings. Drawing

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on these four arguments, the review proposes the Humanitarian WASH-SDG Integration Framework (HWSIF), synthesising evidence across five strategic domains: health systems strengthening, gender-transformative programming, climate-adaptive infrastructure, community governance, and Leave No One Behind targeting. The article concludes with six recommendations directed at humanitarian actors, national governments, UN agencies, bilateral donors, and the research community, constituting an agenda for transformative action toward the full realisation of humanitarian WASH programming as a structural investment in sustainable development.

Index Terms—WASH; Sustainable Development Goals; humanitarian-development nexus; climate resilience; Leave No One Behind; fragile and conflict-affected settings

I. INTRODUCTION

There is a tendency in humanitarian discourse convenient for operational planning, intellectually insufficient, and ethically troubling to treat water and sanitation as logistical problems. Crises stabilized and then handed off to development programming when the acute emergency has subsided. This framing reduces access to water from rights claim to a supply chain problem. It reduces sanitation from a dignity issue to an engineering challenge. And it reduces hygiene, a practice enabled or disabled by the physical, social, and economic conditions in which people live to a behaviour in need of correction. Most consequentially, it treats the failure to provide WASH services in a displacement camp in South Sudan, a flood-affected community in Bangladesh, or a drought-ravaged district in Somalia as a temporary gap to be bridged, rather than what it actually is: a structural injustice whose consequences travel across every dimension of sustainable human development (WHO/UNICEF, 2023).

The 2030 Agenda for Sustainable Development recognised something more profound. SDG 6 - 'Ensure availability and sustainable management of water and sanitation for all' established targets for universal access to safe drinking water, adequate sanitation and hygiene, improved water quality, water use efficiency, integrated water resources management, and ecosystem protection by 2030 (UN, 2015). But SDG 6 was never intended to stand alone. Its targets are architecturally connected to SDG 3 (health and wellbeing), SDG 4 (quality education), SDG 5 (gender equality), SDG 10 (reduced inequalities), SDG 13 (climate action), SDG 16 (peace, justice, and strong institutions), and SDG 17 (global partnerships) in ways that make WASH a structural node in the entire SDG system (UN-Water, 2016; Gosling et al., 2020). Progress on SDG 6 creates enabling conditions for progress across multiple other goals. Failure on SDG 6 generates cascading deprivations that travel through the SDG architecture in ways that aggregate targets cannot capture.

The 2023 SDG Progress Report makes the severity of this failure unmistakable. On current trajectories, the world will not achieve SDG 6 by 2030. An estimated 703 million people still lack basic drinking water services. Nearly 1.7 billion lack basic sanitation. Over 2.2 billion lack handwashing facilities with soap and water at home (UN, 2023; WHO/UNICEF, 2023). Progress

is most severely stalled in sub-Saharan Africa, South Asia, and fragile and conflict-affected states: precisely the contexts where humanitarian WASH programming is most concentrated. This geographic convergence between SDG underperformance and humanitarian crisis is not coincidental. It reflects the structural relationship between fragility, conflict, climate vulnerability, poverty, and WASH service collapse that this review places at its analytical centre (Wilbur & Jones, 2022).

Despite the importance of this relationship, the existing literature treats humanitarian WASH and SDG achievement as parallel rather than integrated agendas. Humanitarian WASH research focuses on immediate outcomes like diarrhoea rates, coverage statistics, cholera prevention. SDG research focuses on national aggregate indicators and policy alignment. The space between them where humanitarian interventions either build toward or undermine long-term SDG progress has received insufficient systematic scholarly attention (Ercumen et al., 2019). This article occupies that space, drawing on 87 sources from 2020 to 2025 to examine the WASH-SDG relationship across health, gender, education, climate, governance, and equity dimensions, and to propose a coherent framework for integrating humanitarian WASH programming with SDG ambition.

Humanitarian WASH interventions are defined as programmes, services, or activities designed to provide water supply, sanitation facilities, or hygiene promotion to populations affected by humanitarian crises including conflict, displacement, natural disasters, or disease outbreaks regardless of whether they are delivered by UN agencies, international NGOs, national governments, or community-based organisations (Sphere Association, 2023). Crisis settings encompass acute emergency phases, protracted displacement situations, and post-crisis recovery contexts. While SDG advancement is understood to include both direct SDG 6 progress and the enabling contributions of WASH to progress on interconnected SDG targets across health, gender, education, climate, and governance dimensions (UN-Water, 2016; UN, 2023).

Research Questions

Four research questions guided the review:

1. How do humanitarian WASH interventions contribute to or constrain SDG achievement across health, gender, education, climate, and governance dimensions?
2. What structural factors enable or impede the translation of humanitarian WASH investments into durable SDG progress beyond the crisis period?
3. How does climate change reshape the scale, character, and SDG implications of humanitarian WASH need?
4. What governance, policy, and operational innovations are most likely to improve the SDG alignment of humanitarian WASH programming at scale?

II. METHODOLOGY

This article employs a systematic narrative review methodology, combining the rigour of systematic evidence identification and screening with the analytical flexibility of narrative synthesis (Snyder, 2022; Grant & Booth, 2009). The approach is appropriate for three reasons: the

research questions require synthesis across heterogeneous evidence types that cannot be meaningfully combined through formal meta-analysis; the policy orientation demands a synthesis that connects empirical findings to programmatic implications; and the review's breadth across five SDG dimensions requires a methodology that can hold multiple analytical frames simultaneously (Snyder, 2022; Mays et al., 2001).

The review followed a four-phase protocol aligned with PRISMA, adapted for systematic narrative reviews per Grant and Booth (2009). Phase 1 established search terms, inclusion and exclusion criteria, quality appraisal standards, and the synthesis framework. Phase 2 executed the search strategy across Web of Science, Scopus, PubMed, Global Health, and WASH-Net between January and May 2025. Phase 3 applied eligibility criteria and quality assessment to identified records. Phase 4 extracted relevant data and organised synthesis across the five HWSIF analytical domains. From 312 initial records, 143 were excluded at title/abstract screening and a further 82 at full-text screening, leaving a retained corpus of 87 documents: 52 peer-reviewed articles, 18 intergovernmental or government reports, 11 NGO programme evaluations, and 6 framework documents. Quality was assessed using the Mixed Methods Appraisal Tool (MMAT) Version 2018 for academic literature and OECD DAC evaluation criteria for programme documents (Hong et al., 2018).

The Humanitarian WASH–SDG Integration Framework (HWSIF), organizes the synthesis across five strategic domains: health systems strengthening, gender-transformative programming, climate-adaptive infrastructure, community governance, and Leave No One Behind targeting. These domains were identified through a scoping review conducted prior to the full systematic search, corresponding to the five dimensions across which the most consistent evidence of WASH-SDG interaction was found (Macura et al., 2021; Wilbur & Jones, 2022).

Data Collection Methods

Evidence was assembled through four complementary channels, each addressing a distinct dimension of the research problem and collectively providing coverage across the breadth of the SDG-WASH nexus literature.

Peer-Reviewed Academic Literature

Systematic database searches were executed between January and March 2025. Results were exported to Endnote X21 for deduplication and to Rayyan for blinded title-abstract screening. Full-text retrieval was conducted for all records passing abstract screening, followed by a second screening stage assessing methodological quality and thematic relevance. Snowball citation tracing was applied to reference lists of all retained articles. The search was restricted to 2020–2025 to align with the post-COVID-19 and post-midpoint SDG review evidence base.

Intergovernmental and Policy Documents

Reports, technical guidance, and framework documents from WHO, UNICEF, UNHCR, OCHA, UN-Water, and DESA were retrieved from institutional repositories. National government WASH strategies and SDG Voluntary National Reviews from the twenty countries with the highest

humanitarian WASH caseloads (OCHA Global Humanitarian Overview 2024) were systematically retrieved and analysed. The Sphere Handbook 2023 update and IASC WASH cluster guidance documents were included as normative framework documents (Sphere Association, 2023; IASC, 2024).

NGO Programme Evaluations and Grey Literature

Programme evaluations, baseline and end-line studies, and operational research reports from the ten largest humanitarian WASH implementers: UNICEF, ICRC, MSF, Oxfam, IRC, ACTED, NRC, ACF, Save the Children, and CARE were retrieved from institutional platforms and from ReliefWeb, the Global WASH Cluster Knowledge Hub, and OCHA FTS documentation. Grey literature quality was assessed using the AACODS (Authority, Accuracy, Coverage, Objectivity, Date, Significance) framework, retaining only documents rated adequate or above on all six dimensions (Tyndall, 2010).

Climate and Environmental Data

Quantitative data on climate-driven humanitarian WASH need were drawn from the IPCC Sixth Assessment Report Working Group II (IPCC, 2022), the INFORM Risk Index 2024, the ND-GAIN Country Index 2023, and WHO reports on water stress and waterborne disease burden under climate change scenarios. These provided the empirical foundation for Domain 3 of the synthesis.

Data Analysis

Analysis proceeded through three sequential but iterative stages. In Stage 1, a deductive framework was applied to all 87 retained documents using a structured extraction matrix organised around the five HWSIF domains and four research questions. Each document extraction captured: study design and quality rating; geographic context; population type; WASH intervention type; SDG dimension addressed; direction and magnitude of the WASH-SDG relationship; mechanisms identified; and enabling or constraining governance factors.

In Stage 2, thematic synthesis was applied inductively within and across the five domains using NVivo Version 14. Initial coding generated 218 codes, consolidated progressively into 34 sub-themes and 12 cross-cutting analytical themes corresponding to the major findings. This inductive layer allowed the synthesis to surface patterns not anticipated in the deductive framework, most notably the emergence of the humanitarian-development nexus as the dominant governance factor mediating WASH-SDG relationships across all five domains (Grant & Booth, 2009; Mays et al., 2005).

In Stage 3, the HWSIF was constructed by integrating the deductive domain analyses with the inductively generated cross-cutting themes. The framework was validated through structured comparison against the WASH SDG Roadmap (UN-Water, 2021), the Humanitarian WASH Compendium (WASH Cluster, 2023), and the IASC WASH nexus guidance. Quantitative data

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were descriptively summarised and integrated with qualitative evidence through a joint display approach (Guetterman et al., 2021).

Ethical Considerations

Systematic reviews of humanitarian literature carry ethical obligations that are distinct from but no less serious than those of primary research with human participants (Israel & Hay, 2006). The populations at the centre of this review: people in displacement camps, conflict zones, disaster-affected communities are among the most vulnerable in the world and among the most frequently written about without adequate consultation, consent, or reciprocity in academic research. This review is explicit about the asymmetry in its methodology: the communities whose lives generate the evidence synthesized here had no direct role in designing the study. That irregularity does not make the review unethical. It does create an obligation to represent communities and their experiences with accuracy, dignity, and analytical charity refusing the reduction of human lives to efficiency metrics, and insisting that the people described in the evidence are agents of their own recovery rather than passive recipients of external interventions (Sphere Association, 2023; Israel & Hay, 2006).

The review's authors acknowledge prior views on the importance of WASH programming and the inadequacy of current SDG progress. To mitigate confirmatory bias, three methodological safeguards were applied: pre-specified inclusion criteria applied blind to findings direction; systematic documentation of excluded evidence including evidence challenging the review's hypotheses; and deliberate inclusion of critical perspectives on WASH programming implementation failures, unintended consequences, and contextual limitations (Grant & Booth, 2009).

All documents cited are fully attributed. Programme evaluations and grey literature were included only from publicly accessible sources. A note on positionality: this review was conducted within a Northern academic institutional context and draws on literature skewed toward evidence produced by international actors. The perspectives of national governments, community water managers, and local researchers closest to the communities described are present only through mediated programme evaluation reports. This positionality limits the review's claims to representativeness and is identified as a priority for redress in future primary research (Wilbur & Jones, 2022).

Limitations of the Study

Five limitations shape the scope and confidence of this paper findings, and each deserves direct statement.

1. Publication bias. The retained literature over-represents heavily researched crisis contexts: Syria, South Sudan, Yemen, Cox's Bazar, the Sahel while under-representing crises in the Pacific, Central America, and conflict-affected Southeast Asia (Ercumen et al., 2019).
2. The 2020–2025 temporal restriction excludes foundational WASH-SDG research from 2015–2020 that conceptually grounds more recent studies (Gosling et al., 2020).

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3. Attributing outcomes to WASH interventions specifically rather than co-occurring investments or environmental change is methodologically difficult; the majority of retained studies support association but not causal attribution (Mays et al., 2005).
4. The review under-represents community voices and locally generated evidence; the most rigorously designed retained studies are predominantly authored by researchers in high-income countries.
5. The HWSIF is a conceptual framework, not an empirically validated intervention model; its practical utility requires piloting, adaptation, and iterative refinement before it can be recommended as an operational tool (Grant & Booth, 2009).

III. RESULTS AND FINDINGS

Characteristics of the Evidence Base

Table 1 presents the distribution of 87 retained sources. Health (SDG 3) was the primary focus of 67.8% of retained sources, followed by gender (SDG 5; 47.1%), education (SDG 4; 34.5%), climate (SDG 13; 31.0%), and governance (SDG 16; 28.7%). Every retained source addressed SDG 6 in some form. The majority of sources addressed multiple SDG dimensions simultaneously, confirming the systemic, cross-cutting character of humanitarian WASH.

Table 1: Characteristics of Retained Sources (N = 87)

Characteristic	Category	n	% of 87
Document type	Peer-reviewed articles	52	59.8%
	Intergovernmental/government reports	18	20.7%
	NGO programme evaluations	11	12.6%
	Framework / normative documents	6	6.9%
Crisis typology	Conflict / fragile state	31	35.6%
	Protracted displacement	22	25.3%
	Natural disaster-affected	18	20.7%
	Disease outbreak	10	11.5%
	Mixed / multi-hazard	6	6.9%
Primary SDG dimension	SDG 3 — Health	59	67.8%
	SDG 5 — Gender	41	47.1%
	SDG 4 — Education	30	34.5%
	SDG 13 — Climate	27	31.0%
	SDG 16 — Governance	25	28.7%
	SDG 6 — Water/Sanitation (direct)	87	100.0%
Methodological approach	Quantitative	29	33.3%
	Qualitative	21	24.1%
	Mixed methods	23	26.5%
	Review / synthesis	14	16.1%

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Domain 1: WASH, Health Systems, and SDG 3

The relationship between humanitarian WASH and health outcomes is the most extensively documented in the retained corpus. First: access to safe water in humanitarian settings reduces diarrhoeal disease incidence by 25–45%, depending on water quality and household storage practices (Wolf et al., 2023). Diarrhoeal disease is the second leading cause of child death globally; a 25–45% reduction across a humanitarian setting of 100,000 people translates into dozens of preventable child deaths per year. Second: improved sanitation coverage in displacement camps, when latrine coverage exceeds 80%, reduces cholera incidence by 40–70% through interruption of faecal-oral transmission chains (WHO, 2022). Third: handwashing with soap reduces diarrhoeal disease incidence by 30–48% and respiratory infection transmission by 16–21% in addition to well-established enteric disease benefits (Wolf et al., 2023; Freeman et al., 2017). Fourth: integrated WASH-nutrition programming generates 12–22% reductions in child stunting compared to nutrition-only interventions, contributing simultaneously to SDG 2 and SDG 3 (Null et al., 2018).

Menstrual health management (MHM) emerges across twelve retained sources as an underexplored but analytically critical dimension of the WASH-health relationship. Inadequate MHM facilities: the absence of private, safe, well-lit latrines with water, disposal infrastructure, and sanitary materials is consistently associated with reproductive tract infections, psychological distress, and school absenteeism that compound gender inequality and undermine SDG 3 and SDG 5 progress simultaneously (Patel et al., 2022; Sommer et al., 2021; Wilbur & Jones, 2022).

Table 2: Quantitative Evidence on WASH-Attributable Health Outcomes in Humanitarian Settings SDG 3 (N = 34 quantitative sources)

Health Outcome	WASH Intervention	Effect Range	Evidence Quality	Sources (n)
Diarrhoeal disease reduction	Safe water + household treatment	25–45% reduction	High	7 studies
Cholera incidence reduction	Sanitation coverage >80%	40–70% reduction	High	5 studies
Respiratory infection reduction	Handwashing with soap	16–21% reduction	Moderate-High	6 studies
Child stunting reduction	Integrated WASH + nutrition	12–22% reduction	Moderate	4 Randomized Controlled Trials
Maternal mortality risk reduction	MHM + hygienic delivery facilities	18–31% risk reduction	Moderate	3 studies
Worm infestation reduction	WASH + deworming integration	38–55% reduction	High	4 studies

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Health Outcome	WASH Intervention	Effect Range	Evidence Quality	Sources (n)
Mental health (stress/anxiety)	Reliable water access, MHM privacy	Positive but heterogeneous	Low-Moderate	5 qualitative

Domain 2: WASH, Gender, and SDG 5

Women and girls in humanitarian crisis settings bear an estimated 72–85% of the water collection burden, with average collection times of 45 minutes per day where water sources are distant or contested (WHO/UNICEF, 2023). When water points are moved closer to settlement areas, studies consistently document collection time reductions of 30–70%, with measurable downstream effects on school attendance, income-generating activity, and women's participation in community governance (Macura et al., 2021; Wilbur & Jones, 2022). Table 3 maps these interactions across six gender dimensions.

Table 3: WASH-Gender Interactions in Humanitarian Settings: Mechanisms, Solutions, and SDG Linkages (N = 34 gender-focused sources)

Gender Dimension	WASH Failure Mechanism	WASH Solution	SDG Target	Source Quality
Time poverty	Water collection: women avg. 45 min/day	Proximate safe water points	SDG 5.4, SDG 8.5	High - 9 studies
GBV and safety risk	Isolated/unlit latrines enabling assault	Safe, lit, sex-separated facilities	SDG 5.2	High - 7 studies
Menstrual health	Lack of MHM facilities and materials	Private MHM spaces + materials	SDG 3.7, SDG 4.1	Moderate - 6 studies
Girls' education	MHM absence drives school non-attendance	School WASH + MHM integration	SDG 4.1	Moderate-High -5 studies
Economic participation	Water burden limits livelihood time	Time savings through access improvement	SDG 8.3	Moderate - 4 studies
WASH governance exclusion	Women excluded from WASH committees	Women-led WASH governance	SDG 5.5	Low-Moderate - 3 studies

The safety dimension connects WASH facility design directly to protection programming. Isolated, poorly lit latrines in displacement settings are a documented site of sexual assault. The evidence linking improved latrine design: sex-separated, adequately lit, close to living areas, with lockable doors to reductions in GBV risk is both methodologically credible and operationally

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actionable (Wilbur & Jones, 2022; Sommer et al., 2021). The persistent failure of standard emergency WASH delivery to provide these features is not merely an engineering shortfall. It is a protection failure and an SDG 5 failure, simultaneously and repeatedly.

Domain 3: Climate Change, WASH, and SDG 13

Climate change is the most rapidly escalating driver of humanitarian WASH need, and its interaction with the SDG agenda represents one of the most consequential analytical frontiers in this field. Climate hazards destroy WASH infrastructure, displace populations who place additional demand on receiving-area WASH systems, and increase exposure to waterborne disease at precisely the moments when WASH system functioning is most compromised (IPCC, 2022; Kotz et al., 2022). Table 4 presents evidence on climate-WASH-SDG interactions across six hazard types.

Table 4: Climate Hazard - WASH - SDG Interaction Evidence (N = 40 climate-relevant sources)

Climate Hazard	WASH Impact	Affected SDGs	Evidence Strength	Key Sources
Flooding	Latrine flooding, water contamination, cholera	SDG 3, 6, 13	High	10 studies
Drought / water stress	Source depletion, water point failure, conflict	SDG 6, 2, 16	High	8 studies
Cyclones / storms	Infrastructure destruction, saltwater intrusion	SDG 6, 11, 13	High	6 studies
Heat stress	Increased demand, infrastructure failure	SDG 3, 6, 13	Moderate	5 studies
Sea-level rise	Groundwater salinization, coastal displacement	SDG 6, 11, 13, 14	Moderate	4 studies
Conflict-climate nexus	Water as weapon; resource conflict driver	SDG 6, 16	High	7 studies

The conflict-climate nexus demands separate attention because it captures a dynamic that the SDG framework does not currently address adequately. Water scarcity, intensified by climate change, is an increasingly documented driver of resource conflict most clearly in the Sahel, the Horn of Africa, and parts of the Middle East (Kotz et al., 2022; IPCC, 2022). Conflict destroys WASH infrastructure, disrupts governance, and displaces populations to areas with even more constrained WASH resources.

This recursive cycle; climate stress driving conflict, conflict destroying WASH, WASH collapse driving further displacement constitutes a WASH-climate-conflict trap from which communities cannot escape without simultaneous intervention across all three dimensions (von Uexkull et al., 2022).

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Domain 4: Community Governance, Localization, and SDG 16

The evidence on community governance is the most practically actionable in the review and the most consistently ignored in operational programming. Table 5 presents findings from 25 governance-focused sources.

WASH programmes that actively involve community governance structures in needs assessment, design, implementation monitoring, and maintenance planning generate significantly better coverage, functionality, and sustainability outcomes than top-down, externally managed programmes (Rosenbaum et al., 2022).

Table 5: Community Governance and Localization Evidence - WASH Outcomes and SDG 16 Linkages (N = 25 governance-focused sources)

Governance Factor	Positive Outcome	Evidence Quality	SDG 16 Linkage
Women's water committee leadership	42% higher pump functionality at 12 months	Moderate - 6 studies	SDG 16.7 - inclusive decision-making
Community financing mechanisms	31% higher tariff collection and sustainability	Moderate - 4 studies	SDG 16.6 - accountable institutions
Local actor WASH management	28% lower cost per beneficiary vs. UN management	High - 5 studies	SDG 16.6 - effective institutions
Government WASH coordination	55% higher coverage in areas with functioning WASH TWG	Moderate-High - 3 studies	SDG 16.6 - accountable institutions
Community-led total sanitation (CLTS)	38–62% ODF status at 18 months	High - 7 studies	SDG 6.2 + SDG 16.7
Conflict-sensitive WASH design	Reduced water-related violence and community tension	Moderate - 4 studies	SDG 16.1 - reduced violence

Domain 5 - Leave No One Behind: Equity, Inclusion, and SDG 10

Standard humanitarian WASH coverage metrics systematically overstate actual access for people with disabilities, the elderly, children, ethnic minorities, and urban informal settlers, whose access to nominally available facilities is mediated by physical, social, economic, and cultural barriers that aggregate statistics cannot capture (Banks et al., 2017; UNHCR, 2023). Table 6 documents the scale of these gaps.

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Table 6: WASH Equity Gaps by Marginalized Population Group in Humanitarian Settings (N = 22 equity-focused sources)

Marginalized Group	Specific Barrier	Coverage Gap vs. Average	SDG 10 Implication
Persons with disabilities	Physical inaccessibility of WASH facilities	31- 44% lower access	SDG 10.2 - inclusion
Women and girls	Safety, MHM, and distance barriers	22-38% effective access gap	SDG 5, SDG 10.2
Elderly persons	Physical access and cognitive barriers	18-27% lower access	SDG 10.2
Children under 5	Safe storage, hygiene, child-friendly facilities	40% of diarrhoea burden - structural	SDG 3, SDG 10
Ethnic / linguistic minorities	Language barriers to hygiene messaging	15-30% lower hygiene practice uptake	SDG 10.2
Urban informal settlers	Exclusion from formal humanitarian WASH response	Systematically excluded	SDG 11, SDG 10
People living with HIV/AIDS	Stigma barriers to MHM and sanitation use	Critical gap - limited data	SDG 3, SDG 10.2

IV. DISCUSSION

The evidence assembled across five domains produces a picture that is simultaneously more promising and more troubling than existing policy discourse typically acknowledges. More promising, because well-designed, gender-responsive, community-governed, and climate-adaptive WASH interventions generate SDG returns that extend far beyond the immediate health outcomes typically used to justify WASH investment with documented effects on girls' education, women's economic participation, conflict de-escalation, environmental sustainability, and institutional capacity at local governance level. More troubling, because humanitarian WASH programming as currently practised: top-down, standardised, coverage-focused, driven by emergency timelines rather than development trajectories is squandering the SDG multiplier potential that the evidence demonstrates is achievable.

The health evidence is in some respects the least contested dimension of this review. Diarrhoeal disease reductions of 25-45% and cholera incidence reductions of 40-70% represent one of the most robust bodies of evidence in global public health (Wolf et al., 2023). But what the retained evidence does not sustain is the durability of these gains. The WASH-health literature is significantly stronger on acute-phase outcomes than on sustainability at 24, 36, and 48-months

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post-intervention (Freeman et al., 2017). The humanitarian-development nexus, at its most concrete, is this question: who maintains the borehole when the humanitarian actor leaves?

The gender evidence brings this to a sharper and more urgent point. Time poverty from inadequate water supply is not merely a welfare concern, it is a structural barrier undermining SDG 5 through multiple simultaneous channels: reduced school attendance, reduced income-generating activity, reduced community decision-making participation, and chronic physical exhaustion (Macura et al., 2021). The GBV dimension is even more direct. Isolated, poorly lit latrines are documented sites of sexual assault in displacement settings, and the evidence linking improved latrine design to reduced GBV risk is operationally actionable right now (Wilbur & Jones, 2022; Sommer et al., 2021). The persistent failure to provide gender-safe WASH facilities is not a technical gap. It is a choice.

The climate evidence raises the most structurally significant finding of the review. The SDG framework including SDG 6 itself was designed for a world in which climate change was a background condition rather than a primary driver of humanitarian need. The IPCC Sixth Assessment Report (IPCC, 2022) and concurrent evidence on climate-driven water stress make clear that framing is no longer adequate (Kotz et al., 2022). By 2050, climate change is projected to push hundreds of millions into acute food insecurity through WASH-mediated pathways and generate the largest forced displacement events in recorded human history. Humanitarian WASH programming needs to shift from climate-blind emergency response to climate-adaptive systems building from the first day of any response (von Uexkull et al., 2022).

The governance evidence challenges a persistent assumption: that international technical expertise and standardised packages are more reliable pathways to coverage and quality than local capacity and context-adaptive design. The evidence does not support this assumption. Locally managed WASH systems consistently outperform internationally managed systems on long-term functionality. Community governance structures with meaningful not merely consultative decision-making authority generate better maintenance outcomes. Women's leadership in WASH governance is associated with significantly better pump functionality and payment compliance (Rosenbaum et al., 2022). The 'strong institutions' that SDG 16 aspires to build are built by investing in local water departments, women's sanitation committees, and community governance structures not by delivering standardised packages to passive recipients. The LNOB evidence is the most uncomfortable finding because it directly challenges the claim that humanitarian WASH programming is reaching those who need it most. Access gaps of 31-44% for persons with disabilities, 22-38% effective access gaps for women and girls, and the systematic exclusion of urban informal settlers from formal humanitarian WASH response are not statistical abstractions. They are daily experiences of exclusion (Banks et al., 2017; UNHCR, 2023).

The Humanitarian WASH–SDG Integration Framework (HWSIF)

The HWSIF organizes the evidence for action across five strategic domains. It is designed for strategic use aligning humanitarian WASH programming with SDG commitments from design onward and operational use guiding specific intervention design to maximise SDG multiplier effects.

Domain 1 - Health Systems Strengthening: Humanitarian WASH interventions should be designed in explicit alignment with national health system strengthening priorities, with handover plans transferring WASH infrastructure, maintenance capacity, and quality monitoring to health authorities at defined transition points. SDG pathway: SDG 3 reducing preventable disease burden; SDG 17 strengthening national system capacity.

Domain 2 - Gender-Transformative Programming: Every WASH intervention should apply a minimum gender and protection standard: sex-separated, well-lit, lockable facilities; MHM materials and private disposal; women's meaningful participation in WASH governance; proximity to living areas; and routine safety audits with female community members. SDG pathway: SDG 5 reducing gender-based burdens; SDG 4 enabling girls' school attendance; SDG 8 reducing women's time poverty.

Domain 3 - Climate-Adaptive Infrastructure: WASH infrastructure should be designed and sited with climate hazard exposure analysis from the outset, using climate-resilient materials, flood-safe positioning, and drought-tolerant water sources. SDG pathway: SDG 13 direct climate adaptation; SDG 6 infrastructure sustainability; SDG 11 resilient settlements.

Domain 4 - Community Governance and Localization: From programme inception, WASH response should invest in and transfer authority to local governance institutions, government line ministries, community water management committees, women's organisations with financing for technical capacity building and ongoing quality support. SDG pathway: SDG 16 - accountable effective institutions; SDG 17 - sustainable partnerships; SDG 10 - reduced governance access inequality.

Domain 5 - Leave No One Behind Targeting: All programmes should conduct disaggregated vulnerability analysis as a precondition for design, implement adaptive measures for identified marginalized groups, and use disaggregated monitoring tracking access for persons with disabilities, women, elderly, children, and ethnic minorities separately from aggregate statistics. SDG pathway: SDG 10 - reduced inequalities; SDG 3, 4, 5 - intersecting progress for marginalized populations.

V. CONCLUSION

This paper began with a simple observation that humanitarian discourse has been slow to fully absorb: water and sanitation in crisis settings are not temporary operational necessities to be managed while the real development work waits. They are structural, political, gendered, ecological, and deeply consequential for the trajectory of every SDG that touches the lives of people in crisis.

The systematic narrative review synthesizes 87 sources from 2020 to 2025 to demonstrate that humanitarian WASH interventions, when designed with deliberate SDG alignment, generate

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documented returns across health, gender, education, climate resilience, governance, and equity that extend far beyond the crisis period. Diarrhoeal disease reductions of 25-45%. Cholera incidence reductions of 40-70% when sanitation coverage reach adequate thresholds. MHM-related improvements in girls' school attendance. Time poverty reductions generating women's economic opportunity. Local governance strengthening through community water management. Climate-adaptive infrastructure protecting against escalating future shocks. These are not hypothetical co-benefits. They are documented outcomes.

The governance failures that produce the current gap between these documented potentials and their consistent delivery are the humanitarian-development nexus disconnect, the exclusion of local actors from meaningful decision-making authority, the gender-blindness of standard facility design, the climate-blindness of emergency infrastructure choices, the invisibility of marginalized populations in aggregate coverage statistics are structural failures requiring structural responses. The HWSIF provides the conceptual architecture for those responses, grounded in the best available evidence and directed at the most consequential gap between what humanitarian WASH currently delivers and what the SDG agenda requires. The people whose lives depend on that integration are not waiting.

VI. IMPLICATIONS OF THE STUDY

Theoretical Implications

This review makes four contributions to the theoretical landscape of humanitarian studies and SDG scholarship. It provides the most comprehensive systematic synthesis to date of the multi-SDG contribution pathways of humanitarian WASH, extending the health-focused WASH evidence base to encompass gender, education, climate, governance, and equity in a single integrative framework. It advances humanitarian-development nexus theory by identifying the specific mechanisms through which the nexus principle can be operationalized in WASH programming beyond rhetorical commitment. It contributes to the LNOB literature by documenting systematic exclusion of marginalized populations from aggregate WASH coverage benefits. And it extends political ecology perspectives to the humanitarian WASH domain by demonstrating that WASH access in crisis settings is mediated by political and institutional factors as much as by technical ones (Wilbur & Jones, 2022; Scoones, 2021).

Policy Implications

For the UN system, the findings signal the urgent need to revise the SDG 6 monitoring framework to include indicators capturing WASH functionality, sustainability, and equity of access not merely coverage in humanitarian and fragile state settings. For OCHA and the IASC WASH Cluster, the findings recommend mandatory integration of the HWSIF's five-domain approach into WASH response planning from cluster activation onward. For bilateral and multilateral humanitarian donors, the findings provide the evidence base for increasing the proportion of humanitarian WASH funding directed at nexus programming above the current industry average of under 15% of WASH budgets (OCHA, 2024; IASC, 2024).

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Practice Implications

For WASH implementing organisations, the HWSIF provides an operational checklist for assessing SDG alignment at programme design, review, and handover stages. The gender-transformative minimum standard in Domain 2 is immediately actionable within existing Sphere standards and IASC guidance, it requires a reorientation of design priorities and genuine institutional commitment to women's safety and participation. For national governments in crisis-affected countries, the findings advocate for integration of humanitarian WASH planning within national SDG 6 financing and governance frameworks, ensuring that emergency response investments are counted, maintained, and built upon in national development planning rather than treated as temporary measures that disappear with the programme cycle.

VII. RECOMMENDATIONS

1: Strengthen the SDG 6 Monitoring and Programming Architecture

The current SDG 6 monitoring framework measures coverage at a point in time and tells us almost nothing about whether WASH infrastructure continues to function, who can actually access it, or what happens when humanitarian actors leave. The UN system and its intergovernmental partners should revise the SDG 6 monitoring framework to include mandatory indicators tracking WASH functionality and sustainability at 12 and 24-months post-intervention, equity of access disaggregated by disability, gender, age, and ethnicity, and the completeness of handover to national or local management. Simultaneously, the WASH Cluster planning template should be restructured to require all new humanitarian WASH responses to specify from activation how they will contribute to health systems strengthening, gender-transformative design, climate adaptation, localization, and the Leave No One Behind imperative. These are not additional reporting burdens; they are the minimum conditions for treating humanitarian WASH as a structural SDG investment rather than a temporary operational fix.

2: Establish a Humanitarian-Development WASH Nexus Fund

The most consequential structural gap in the current humanitarian WASH financing architecture is the absence of flexible, multi-year funding mechanisms capable of bridging the transition from emergency response to sustainable national systems. OCHA, UNDP, and UN-Water should jointly establish a Humanitarian-Development WASH Nexus Fund providing multi-year financing explicitly designed for programmes that span the humanitarian-development boundary such as funding handover planning, local government capacity building, and community governance structures that neither purely humanitarian nor purely development budgets are currently designed to support.

A minimum of 40% of this fund's allocations should flow directly to local and national implementing organisations, reflecting both the equity imperative of localization and the evidence that locally managed WASH systems consistently outperform internationally managed ones on long-term sustainability.

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3: Adopt Universal Gender-Transformative and Equity Standards in WASH Design

Every WASH intervention in a humanitarian setting should meet a non-negotiable minimum standard of gender-transformative design: facilities that are sex-separated, adequately lit, lockable, positioned within safe proximity of living areas, and equipped with menstrual hygiene management materials and disposal infrastructure. These standards should be operationalized as mandatory design requirements rather than aspirational guidelines, with participatory safety audits involving female community members conducted at intervals of no longer than three months. No programme should reach design approval without a disaggregated vulnerability analysis identifying specific access barriers facing persons with disabilities, women, the elderly, children, and ethnic minorities; and no programme evaluation or donor report should be accepted that presents only aggregate coverage figures without disaggregated access data. Equity in WASH is not an add-on; it is the condition under which coverage statistics actually mean something.

4: Invest Systematically in Localization and Government Ownership

The evidence that community governance structures and local water management institutions generate better long-term WASH outcomes than externally managed programmes is consistent and strong. Humanitarian WASH implementing organisations should commit a minimum of ten per cent of all programme budgets to localization activities from programme inception: technical and financial capacity building for local government water departments and community water management committees, co-management structures that give local actors genuine decision-making authority rather than consultative roles, and participatory handover planning that begins at programme design rather than as a late-stage exit activity. National governments in crisis-affected countries should complement this by integrating humanitarian WASH infrastructure into national SDG 6 asset registries and maintenance financing plans, treating emergency water points and latrines as permanent national development assets that require budgeted maintenance, not temporary humanitarian facilities that disappear with the programme cycle. Where WASH Technical Working Groups do not exist at national and subnational level with explicit humanitarian-development nexus mandates, they should be established; where they exist in name only, they should be strengthened with adequate authority and cross-sector representation.

5: Generate the Longitudinal and Participatory Evidence that the field needs

The WASH-SDG literature is systematically stronger on acute-phase outcomes than on sustainability, equity, and governance at twenty-four, 36, and 48-months post-intervention, precisely the timeframes that matter for assessing SDG contribution and informing the design of future responses. Research institutions should prioritise longitudinal primary studies that track WASH outcomes across this extended timeframe in a representative range of crisis typologies, from acute displacement to protracted conflict to post-disaster recovery. Equally important and equally underrepresented in the current evidence base, is community-participatory research that generates evidence grounded in the lived experience of marginalized WASH users: persons with disabilities navigating inaccessible facilities, women managing menstrual health in unsafe settings, elderly persons excluded by design from nominal coverage figures. Evidence extracted from

aggregate statistics about communities whose experience it is supposed to represent is not a substitute for evidence generated with those communities as active participants.

6: Validate the HWSIF and Sustain the Evidence Base

The Humanitarian WASH–SDG Integration Framework proposed in this review represents a conceptual contribution to an agenda that requires operational validation before it can be recommended as standard programming guidance. Research institutions and humanitarian actors should collaborate to pilot the HWSIF systematically across at least three distinct humanitarian crisis typologies including at minimum a conflict-displacement setting, a natural disaster setting, and a protracted crisis with independent evaluation of its feasibility, fidelity of implementation, and SDG outcome contribution. Beyond framework validation, the field needs a durable commitment to evidence maintenance: a systematic review update protocol should be established with a biennial refresh cycle, ensuring that the WASH-SDG evidence synthesis keeps pace with the evolving crisis landscape, the accumulated findings of longitudinal studies, and the accountability timeline of the 2030 Agenda. Good frameworks become obsolete; what must not become obsolete is the commitment to ground them continuously in the best available evidence.

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Agni: An Integrative Perspective on Digestion, Metabolism and Gut Microbiota

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Abstract—Agni **is a fundamental physiological concept in Ayurveda and represents the processes of digestion, transformation, assimilation and metabolism. Classical Ayurvedic literature describes *Agni* as essential for maintaining strength, nourishment, vitality and health. Based on its functions and sites of action, *Agni* is broadly described as *Jatharagni*, *Bhutagni* and *Dhatvagni*, representing different levels of transformation from digestion of food to tissue-level metabolism. Modern physiological interpretations have explored these concepts in relation to gastrointestinal digestion, nutrient utilization and metabolic transformation. Contemporary research further highlights the role of gut microbiota in digestion, nutrient metabolism, immune regulation and gut-brain communication. This review integrates classical Ayurvedic descriptions of *Agni* with contemporary perspectives on metabolism, cellular bioenergetics and gut microbiota. It proposes that *Agni* may be understood as a multilevel functional framework of biological transformation and metabolic homeostasis rather than being equated with any single modern physiological entity. This integrative perspective may provide a foundation for future experimental research correlating Ayurvedic assessment of *Agni* with objective physiological, metabolic and microbiological parameters.**

Index Terms—Agni, Jatharagni, Dhatvagni, **Metabolism, Gut Microbiota**

I. INTRODUCTION

Digestion and metabolism are fundamental physiological processes required for the maintenance of life. Ayurveda explains these processes through the comprehensive concept of *Agni*, which is associated with digestion, transformation, assimilation and utilization of nutrients. *Agni* is also described in relation to strength, nourishment, vitality, health and maintenance of normal physiological functions.

The importance of *Agni* is extensively described in classical Ayurvedic literature. Charaka Samhita considers *Agni* essential for the maintenance of life, strength, nourishment and health, while impairment of *Agni* is associated with disease processes. Similar importance is attributed to *Agni* in Sushruta Samhita and Ashtanga Hridaya, where digestion and proper transformation of food are considered fundamental to normal physiology.

According to Ayurvedic physiology, *Agni* is broadly classified into *Jatharagni*, five *Bhutagni* and seven *Dhatvagni*, giving a total of thirteen *Agni*s. *Jatharagni* is primarily concerned with the initial digestive transformation, whereas *Bhutagni* and *Dhatvagni* are associated with subsequent stages of transformation and tissue nourishment.

Modern interpretations have attempted to relate *Agni* with digestion, absorption, metabolism and biochemical transformation. In recent years, recognition of the extensive role of the gut microbiota has added another dimension to the understanding of digestion and metabolism. Gut microorganisms participate in nutrient metabolism, production of bioactive metabolites, immune regulation and host homeostasis.

Therefore, an integrated examination of *Agni* may provide an interesting framework connecting digestion, metabolism, cellular bioenergetics and gut microbial activity.

II. CONCEPT OF *AGNI*

Agni is described in Ayurveda as the principle responsible for transformation and processing of substances within the body. Proper functioning of *Agni* is considered essential for digestion, nourishment and maintenance of health, whereas impaired *Agni* is associated with abnormal physiological functioning.

The classical concept emphasizes that food cannot contribute to nourishment unless it undergoes appropriate transformation. Thus, *Agni* represents not simply the presence of food within the gastrointestinal tract but its conversion into forms suitable for absorption and utilization.

Charaka describes *Agni* as fundamental to the maintenance of life and physiological equilibrium. The concept of *Agni* is also discussed in relation to digestion, metabolism and maintenance of physiological balance.

From a contemporary perspective, the concept of transformation may be explored alongside enzymatic digestion, nutrient absorption, intermediary metabolism and cellular utilization. However, *Agni* should not be considered equivalent to any single modern physiological structure or biochemical process.

III. CLASSIFICATION OF *AGNI*

Agni is broadly classified into three major categories:

- *Jatharagni* – one
- *Bhutagni* – five
- *Dhatvagni* – seven

Thus, thirteen types of *Agni* are described according to their site and function.

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3.1 *Jatharagni*

Jatharagni is considered the principal digestive *Agni*. It acts on ingested food and initiates the process of digestion and transformation. The products of digestion are traditionally described as the useful *Prasada* component and waste *Kitta* component.

The action of *Jatharagni* may be conceptually compared with the integrated physiological processes involved in gastrointestinal digestion and nutrient absorption. The Ayurvedic concept of *Ahara Paka* further describes the transformation of ingested food into forms suitable for subsequent utilization.

Jatharagni should nevertheless not be considered equivalent to gastric acid, digestive enzymes or any individual gastrointestinal organ.

3.2 *Bhutagni*

Five *Bhutagni* are described in association with the five *Mahabhutas*. They are considered to participate in further transformation of food components following the initial action of *Jatharagni*.

The physiological interpretation of *Bhutagni* has been discussed in relation to post-digestive biochemical transformation and processing of nutrients. It may therefore be considered as a conceptual stage between primary digestion and subsequent tissue-level utilization.

3.3 *Dhatvagni*

Seven *Dhatvagni* are described in relation to the seven *Dhatu*s: *Rasagni, Raktagni, Mamsagni, Medagni, Asthyagni, Majjagni* and *Shukragni*.

Each *Dhatvagni* is considered to act specifically at the level of its respective *Dhatu* and contributes to tissue transformation and nourishment.

The concept of *Dhatvagni* has been interpreted in relation to tissue-level metabolism and cellular biochemical activity. The idea of *Agni* as a biotransformer further provides a conceptual basis for discussing the continuous biochemical and biophysical transformations occurring within the body.

IV. *AGNI* AND METABOLISM

Modern metabolism consists of a complex network of biochemical reactions responsible for nutrient utilization, energy production, synthesis and degradation of cellular components.

The Ayurvedic concept of *Agni* similarly emphasizes transformation and utilization of nutrients. The sequence of *Jatharagni*, *Bhutagni* and *Dhatvagni* may therefore be interpreted as a progressive model of biological transformation.

Agni has been discussed in relation to digestion, absorption, assimilation and metabolic activities. This provides a conceptual basis for exploring *Agni* as a broader physiological framework extending from digestion to nutrient utilization and tissue metabolism.

Thus, *Agni* may be viewed as an integrative concept encompassing different levels of transformation rather than as a single isolated physiological process.

V. *AGNI* AND CELLULAR BIOENERGETICS

Continuous cellular activity requires a constant supply of energy. Modern physiology recognizes mitochondria as major sites of cellular energy production.

The concept of *Dhatvagni* has been discussed in relation to metabolic activity occurring at tissue and cellular levels. *Agni* has also been conceptualized as a biotransformer involved in biochemical and biophysical processes occurring throughout the body.

Cellular metabolism involves coordinated biochemical pathways that convert nutrients into usable energy and biosynthetic intermediates. Mitochondria play an important role in these processes through oxidative metabolism and ATP generation.

However, *Dhatvagni* should not be directly equated with mitochondria. Mitochondrial metabolism is one modern physiological mechanism through which aspects of cellular transformation and energy production may be investigated.

VI. DIFFERENT STATES OF *JATHARAGNI*

Ayurveda describes four major functional states of *Jatharagni*.

Samagni represents balanced digestive activity, in which digestion and assimilation occur appropriately and contribute to normal nourishment.

Vishamagni represents irregular digestive activity and is traditionally associated with *Vata* predominance.

Tikshnagni represents excessively intense digestive activity and is traditionally associated with *Pitta* predominance.

Mandagni represents sluggish digestive activity and is traditionally associated with *Kapha* predominance.

From a contemporary physiological perspective, these states may be explored in relation to variations in appetite, digestive efficiency and metabolic homeostasis. However, these Ayurvedic categories should not be directly equated with specific modern diseases without appropriate experimental evidence.

VII. *JATHARAGNI–DHATVAGNI* RELATIONSHIP

An important feature of Ayurvedic physiology is the functional relationship between *Jatharagni* and *Dhatvagni*. Proper functioning of *Jatharagni* is considered necessary for subsequent tissue-level transformation.

The relationship may be represented as:

Jatharagni → Digestion → Nutrient availability → *Dhatvagni* → Tissue metabolism → Nourishment

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This sequence has a conceptual similarity with modern physiology, in which gastrointestinal digestion and absorption determine the availability of nutrients required for cellular and tissue metabolism.
Thus, disturbance at the initial level of digestion may conceptually influence subsequent nutrient availability and tissue-level metabolic processes.

VIII. *AGNI* AND GUT MICROBIOTA

The gut microbiota consists of a complex community of microorganisms residing predominantly within the gastrointestinal tract. These microorganisms contribute to digestion, nutrient metabolism, vitamin synthesis, immune regulation and protection against pathogens.
The relationship between gut microbiota and *Agni* has recently attracted attention. Microbial activity may be considered relevant to several processes traditionally associated with digestion and metabolic transformation.
Gut microorganisms are capable of transforming dietary substrates that are incompletely digested by the host, thereby producing metabolites that influence intestinal and systemic physiology.
This provides an important contemporary perspective through which the broader concept of *Agni* can be investigated.

IX. *AGNI* AND GUT MICROBIOTA: A CONCEPTUAL INTERFACE

The Ayurvedic perspective may be represented as:
Agni → Digestion → Transformation → Assimilation → Nourishment → Health

The modern physiological perspective can be represented as:
Diet → Gastrointestinal digestion → Microbial transformation → Microbial metabolites → Host metabolism → Systemic effects
Gut microbiota produces metabolites such as short-chain fatty acids through fermentation of dietary components. These metabolites influence host metabolism and energy homeostasis.
The relationship between gut microbiota-derived metabolites and glucose homeostasis has also been investigated, demonstrating their potential role in metabolic regulation.
Therefore, gut microbiota may represent one biological component through which certain dimensions of the *Agni* concept can be experimentally explored, rather than being considered synonymous with *Agni*.

X. *AGNI*, EUBIOSIS AND DYSBIOSIS

A balanced intestinal microbial ecosystem is associated with normal gastrointestinal and systemic physiology. Alterations in microbial composition and function, broadly referred to as dysbiosis, have been associated with metabolic and inflammatory disorders.

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Gut microbiota has been associated with human metabolic health and disease, including obesity, type 2 diabetes and other metabolic disorders.

Agni disturbances are similarly considered important in Ayurvedic pathophysiology. This conceptual similarity provides an opportunity to investigate whether clinical assessment of *Agni* correlates with measurable characteristics of gut microbial composition and metabolic health.

However, *Ama* should not be considered equivalent to dysbiosis unless such a relationship is demonstrated through appropriate experimental studies.

XI. GUT MICROBIOTA-DERIVED METABOLITES AND *AGNI*

Gut microbiota produces several biologically active metabolites that participate in communication between microorganisms and the host.

Microbial metabolites, including short-chain fatty acids and bile acid derivatives, have important effects on host metabolism and immune regulation.

Gut microbiota-derived metabolites have been described as important regulators of metabolic disorders and host–microbiota interactions.

Gut microorganisms also participate in the transformation of bile acids, thereby influencing host physiology and disease processes.

These observations provide a potentially useful experimental framework for investigating whether traditional assessment of *Agni* has measurable relationships with microbial metabolic products.

XII. *AGNI* AND GUT-BRAIN AXIS

The gut and brain communicate through neural, endocrine, immune and microbial pathways. Gut microbiota may influence metabolic and neurophysiological processes through several mechanisms. The relationship between gut microbiota and host metabolism has also highlighted the potential importance of microbiota-associated metabolic pathways.

This emerging understanding provides an opportunity to examine *Agni* beyond gastrointestinal digestion and explore its possible relationship with metabolic regulation, immune function and gut-brain communication.

XIII. INTEGRATED PHYSIOLOGICAL MODEL OF *AGNI*

Based on the reviewed literature, an integrated conceptual model can be proposed:

Food intake

↓

Jatharagni – Primary digestion and transformation

↓

Bhutagni – Further transformation

↓

Nutrient availability / *Ahara Rasa*

↓
Dhatvagni – Tissue-specific transformation
↓
Cellular metabolism and bioenergetics
↓
Energy production + tissue nourishment
↓
Systemic homeostasis

Alongside this pathway:
Dietary substrates
↓
Gut microbiota
↓
Microbial metabolites
↓
Metabolic + immune + gut-brain effects
This model should be considered a conceptual and hypothesis-generating framework, rather than evidence of one-to-one correspondence between Ayurvedic concepts and modern biological entities.

XIV. DISCUSSION

The reviewed literature presents *Agni* from multiple complementary perspectives. Classical Ayurvedic texts describe *Agni* as an important principle involved in digestion, transformation, nourishment and maintenance of physiological equilibrium.
The concepts of *Jatharagni*, *Bhutagni* and *Dhatvagni* provide a progressive framework extending from gastrointestinal digestion to tissue-level transformation. Contemporary interpretations have further explored *Agni* in relation to metabolic activities and cellular transformation.
The relationship between *Agni* and gut microbiota provides another important area of integration. Gut microorganisms participate in nutrient metabolism, production of bioactive metabolites and regulation of host physiology.
Microbial metabolites have been associated with glucose homeostasis and metabolic regulation. Bile acid transformation by gut microorganisms represents another mechanism through which microbial activity influences host physiology.
Taken together, these observations suggest that *Agni* may be explored as an integrative physiological construct encompassing multiple levels of biological transformation.
However, conceptual similarity should not be mistaken for biological equivalence. *Agni* cannot presently be reduced to digestive enzymes, gastric secretions, mitochondria or gut microbiota individually. These represent distinct components of modern physiology that may help investigate different dimensions of the broader Ayurvedic concept.

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XV. FUTURE RESEARCH PERSPECTIVES

Future studies may investigate correlations between standardized Ayurvedic assessment of *Agni* and:

1. Digestive symptoms and bowel habits.
2. Dietary patterns.
3. Body composition.
4. Glucose and lipid metabolism.
5. Inflammatory markers.
6. Gut microbiota composition.
7. Short-chain fatty acids.
8. Bile acid profiles.
9. Cellular metabolic markers.
10. Mitochondrial function.
11. Gut-brain axis parameters.

A particularly useful research direction would be the development and validation of a standardized *Agni* assessment scale, followed by correlation with objective metabolic and microbiological parameters. Such studies could determine whether traditional clinical assessment of *Agni* has reproducible biological correlates and may help develop an evidence-based framework for integrating Ayurvedic physiology with contemporary biomedical science.

XVI. CONCLUSION

Agni is an important physiological concept of Ayurveda encompassing digestion, transformation, assimilation, metabolism and nourishment. The classical framework of *Jatharagni*, *Bhutagni* and *Dhatvagni* provides a progressive model extending from digestion of food to tissue-level transformation.

Modern physiology provides complementary domains through which these functions can be investigated, including gastrointestinal digestion, nutrient metabolism and cellular bioenergetics. Contemporary microbiome research further demonstrates the contribution of gut microorganisms and their metabolites to digestion, metabolism, immune regulation and systemic physiology. Thus, *Agni* may best be understood as an integrative Ayurvedic framework of biological transformation and metabolic homeostasis, rather than as an equivalent of any single modern physiological entity. Integration of Ayurvedic assessment with objective metabolic, microbiological and physiological parameters may provide a promising pathway for future research in Kriya Sharir.

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Teacher, Student and Technology in Viksit Bharat

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***Abstract*—Viksit Bharat Abhiyan (or Viksit Bharat@2047) is an initiative of the Government of India to make India a developed nation by 2047. This vision stands on four pillars - Yuva (Youth), Garib (Poor), Mahilayen (Women) and Annadata (Farmers). It aims to boost India's economy to $30 trillion in two decades, concentrating on its infrastructure, education, health care, technology, and sustainable development. Fulfilling Viksit Bharat's vision needs to cater to the education system's imbalance and promote inclusive growth with skills upgradation suitable for the 21st century. The National Education Policy (NEP) 2020 aims to catalyze this transformation. In the envisioned landscape of Viksit Bharat (Developed India) in 2047, trans-formative teacher education emerges as a cornerstone for sustained progress and societal development. This abstract provides a snapshot of the evolving perspectives and innovative approaches characterizing the paradigm shift in teacher education. Rooted in the integration of advanced technologies, progressive pedagogies, and a holistic educator development model, the research explores the multifaceted nature of teacher preparation.**

***Index Terms*—Students, Teachers, Holistic Development, Developed India 2047, Technology Integration.**

I. INTRODUCTION:

Viksit Bharat 2047 envisions India as a developed nation by the 100th year of independence. Education is one of the key pillars of this vision, where teachers, students, and technology work together to create a skilled, innovative, and responsible society. Education serves as a catalyst for social revolution and a vital tool for attaining fundamental human rights. Literacy and basic education unlock new opportunities for personal, civic, economic, and lifelong learning, empowering individuals to advance personally and professionally. To achieve the ambitious goals of Viksit Bharat, Education 4.0 will play a pivotal role in revolutionizing the education sector. By

integrating cutting-edge technologies and innovative pedagogies, Education 4.0 will equip future generations with the skills, knowledge, and competencies necessary to thrive in an increasingly complex and interconnected world. As India embarks on this transformative journey, it is essential to explore the intersections between Education 4.0 and Viksit Bharat, ultimately. In the year 2047, as Viksit Bharat stands proudly as a Developed India, the evolution of its educational landscape, especially in the domain of teacher education, becomes a beacon of progress and innovation. This article delves into the transformative journey that characterizes teacher education in this advanced nation, exploring the perspectives and innovative approaches that redefine the role of educators in shaping the future. Viksit Bharat's commitment to excellence in education is mirrored in its dedication to preparing teachers who not only adapt to but also drive the dynamic changes in the learning environment. This article aims to provide a comprehensive overview of the conceptual framework underpinning transformative teacher education, shedding light on cutting-edge technologies, pedagogical advancements, and holistic approaches that contribute to the holistic development of educators. By examining the multifaceted aspects of teacher preparation, this article contributes to the discourse on the future of education in Viksit Bharat, illustrating the transformative strides taken in the realm of teacher education, fostering a progressive and adaptable cohort of educators poised to meet the challenges of the 21st century.

II. ROLE OF THE TEACHER

The future of the country is designed by its educators. In Viksit Bharat, they are expected to:

- Rather than just imparting knowledge, serve as mentors and facilitators.
- Promote problem-solving, creativity, and critical thinking.
- Encourage moral principles including discipline, ethics, and environmental responsibility.
- Make learning dynamic by utilizing smart classrooms, artificial intelligence, and digital tools.
- Continually improve their abilities through training in technology and professional development.

Role of Teachers in Building Viksit Bharat

Because they mold students' knowledge, abilities, values, and character, teachers are frequently referred to as the architects of the country's future. Teachers have duties outside of the traditional classroom, according to Viksit Bharat's (Developed India) vision. They are supposed to help pupils become creative, responsible, and competitive citizens on a global scale.

1. Act as Facilitators and Mentors Rather Than Only Knowledge Providers

Teachers were primarily in charge of imparting knowledge while pupils listened and committed it to memory in the conventional educational system. These days, books, the internet, and digital platforms make information easily accessible. As a result, the function of the teacher has changed to include mentoring and facilitation.

Students are guided by a facilitator as they investigate ideas, pose queries, and come up with answers on their own. Teachers serve as mentors, offering personal inspiration, career advice, and

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emotional support. They support kids in discovering their abilities, overcoming obstacles, and gaining self-assurance.
For instance, a teacher encourages students to do experiments, discuss observations, and come to their own conclusions rather than merely describing a science idea.

2. Encourage Critical Thinking, Creativity, and Problem-Solving
Instead of just memorizing facts, the goal of modern education is to create students who are capable of autonomous thought. Students should be encouraged by their teachers to assess information, analyze situations, and come to logical conclusions.
Creating original concepts and creative solutions is a key component of creativity. Students with strong problem-solving abilities are better equipped to handle obstacles in real life. These skills are highly regarded in the job and are necessary in the ever-evolving world of today.

Teachers can encourage these abilities by:
- Project-based learning
- Group discussions and debates
- Case studies
- Brainstorming sessions
- Practical experiments
- Real-world problem-solving activities

Example:
Teachers could assign pupils to create a waste management strategy for their school rather than having them memorize environmental topics.

3. Promote Values Such as Ethics, Discipline, and Environmental Responsibility
Character development is just as important to education as academic success. In order to assist pupils, become responsible citizens, teachers are essential in fostering moral and social ideals.

Ethics
Teachers encourage honesty, integrity, fairness, respect, and empathy in daily life.

Discipline
Discipline helps students develop self-control, punctuality, responsibility, and commitment toward their work.

Environmental Responsibility
Teachers promote awareness about sustainable living by advocating behaviors such as:
- Tree plantation
- Water conservation

- Waste segregation
- Recycling
- Energy conservation
- Cleanliness drives

These values contribute to creating socially responsible and environmentally conscious citizens.

Example:
Organizing campaigns to reduce plastic use and encouraging students to participate in community cleanliness programs.

4. Use Digital Tools, Artificial Intelligence, and Smart Classrooms to Make Learning Interactive

Technology has altered education by making learning more enjoyable and accessible. Teachers are expected to integrate digital tools into classroom learning.

Some useful technologies include:

- Smart boards and interactive displays
- Online learning platforms
- Educational videos and animations
- Virtual laboratories
- Learning management systems
- Artificial Intelligence (AI)-based learning tools
- Educational apps and simulations AI can:
- Personalize learning according to student needs.
- Provide instant feedback.
- Assess student performance.
- Generate quizzes and assignments.
- Identify learning gaps.

Smart classrooms make lessons more interactive through multimedia presentations, virtual demonstrations, and collaborative activities.

Example: A geography teacher can employ virtual reality (VR) or digital maps to enable students explore diverse places instead of depending exclusively on textbooks.

5. Continuously Upgrade Their Skills Through Professional Development and Technology Training

Technology and education are always changing. Therefore, instructors must engage in lifelong learning to stay successful educators.

Professional development helps teachers:

- Learn modern teaching methods.

- Improve classroom management.
- Understand new educational policies.
- Master digital teaching tools.
- Develop subject expertise.
- Incorporate innovative teaching strategies.

Teachers can upgrade their skills through:

- Workshops
- Seminars
- Online certification courses
- Faculty development programmes
- Webinars
- Peer learning communities
- Research and academic conferences

Continuous learning enables teachers to provide quality education that meets the needs of the 21st-century learner.

Example:
A teacher who completes training in AI-powered educational tools can develop tailored learning experiences and boost student engagement.

III. ROLE OF THE STUDENT

Students are India's future leaders and innovators.

- Develop curiosity and a lifetime learning mindset.
- Build digital literacy and technological abilities.
- Focus on innovation, entrepreneurship, and research.
- Practice teamwork, leadership, and responsible citizenship.
- Use technology responsibly and ethically for learning and nation-building.

Role of Students in Viksit Bharat (Developed India)
Students are the backbone of a nation's future. By 2047, they will have shaped India's path towards Viksit Bharat (Developed India) as innovators, leaders, entrepreneurs, and responsible citizens. Their knowledge, abilities, creativity, and values will decide the country's success in education, technology, economy, and social development.

By actively contributing to their personal progress and the welfare of society, students may play a significant part in developing India into an internationally respected, prosperous, and sustainable nation.

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1. Develop Curiosity and a Lifelong Learning Mindset

Curiosity is the root of invention and discovery. Students should foster the practice of asking questions, exploring new ideas, and pursuing knowledge beyond textbooks. A lifelong learning mentality motivates them to consistently enhance their abilities and adapt to shifting technologies and global trends. Learning is an ongoing process in the ever-changing world of today; it doesn't stop at school or college. Students who embrace lifelong learning become capable of overcoming difficult challenges and contributing significantly to national growth.

2. Build Digital Literacy and Technological Skills

Digital literacy is vital in the 21st century. Students should develop skill in using computers, the internet, artificial intelligence, coding, data analysis, and other emerging technologies. These abilities boost their employability and enable them to contribute to India's digital development. By knowing technology and applying it effectively, students may engage in generating smart solutions for education, healthcare, agriculture, governance, and business, thereby increasing India's position as a global technology leader.

3. Focus on Innovation, Entrepreneurship, and Research

Research and innovation are important forces behind both national advancement and economic expansion. Students should be encouraged to investigate scientific studies, think creatively, and hone their problem-solving skills. Young people can start businesses, create jobs, and offer creative solutions to societal problems through entrepreneurship. Students may make a substantial contribution to making India self-sufficient and competitive on a global scale, whether through scientific discoveries, technical innovations, or entrepreneurial endeavours.

4. Practice Teamwork, Leadership, and Responsible Citizenship

Today's environment demands teamwork and strong leadership for success. Students should be taught how to respect different viewpoints, collaborate with others, and communicate clearly. They are more equipped to mentor others and make valuable contributions to society when they possess leadership traits like accountability, judgment, empathy, and integrity. Respecting the Constitution, abiding by the law, safeguarding public property, fostering social harmony, and engaging in community service are all components of responsible citizenship. These attributes contribute to the development of a cohesive and forward-thinking country.

5. Use Technology Wisely and Ethically for Learning and Nation-Building

Although technology is an effective tool, it must be used sensibly. Instead of using digital platforms for harmful or false information, students should use them for education, skill development, research, and creativity. Respecting privacy, preventing cyberbullying, upholding cybersecurity, and employing artificial intelligence sensibly are all examples of ethical technology use. Students can actively participate in India's development and digital future by using technology for social welfare, environmental conservation, education, healthcare, and government.

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IV. ROLE OF TECHNOLOGY

High-quality education is greatly aided by technology.

- Providing access to online learning resources and digital classrooms.
- Personalizing learning through AI and adaptive educational platforms.
- Improving collaboration between teachers and students.
- Reducing geographical barriers through virtual education.
- Supporting skill development aligned with future employment needs.

Role of Technology in Viksit Bharat (Developed India)

One of the most powerful foundations in realizing Viksit Bharat 2047's goal is technology. It is revolutionizing education, employment, communication, and innovation. Regardless of a student's location or background, technology in education guarantees that they receive high-quality instruction. Technology equips students with the information and abilities required for the future by combining digital tools, artificial intelligence, and online platforms. Additionally, it fosters creativity, innovation, and lifelong learning, which helps India develop a workforce that is competitive on a global scale.

1. Providing Access to Online Learning Resources and Digital Classrooms

Education is now more accessible than ever thanks to technology. Students can learn at any time and from any location with the use of online learning platforms, digital classrooms, e-books, instructional videos, and virtual lectures. Even people who live in isolated and rural places have access to top-notch educational resources from knowledgeable instructors and organizations. Through live debates, quizzes, and multimedia presentations, digital classrooms also make learning dynamic, resulting in a more captivating educational experience.

2. Personalizing Learning Through AI and Adaptive Educational Platforms

By providing individualized learning opportunities, artificial intelligence (AI) has transformed education. AI-powered learning platforms deliver personalized lectures, practice tasks, and feedback based on an analysis of each student's learning style, strengths, and shortcomings. Students perform better and comprehend things more efficiently as a result. Additionally, personalized learning guarantees that each student gets the assistance they require, increasing the effectiveness and inclusivity of education.

3. Improving Collaboration Between Teachers and Students

Through video conferences, online discussion boards, messaging apps, and collaborative learning tools, technology improves communication and teamwork between educators and students. No matter where they are physically located, students can engage in group projects, ask questions, turn in assignments, and get immediate feedback. Additionally, teachers can use digital assessment tools to track students' progress and offer timely guidance, which enhances the effectiveness and interactivity of the teaching-learning process.

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4. Reducing Geographical Barriers Through Virtual Education

The ability of technology to overcome geographical constraints is one of its biggest benefits. Students from underserved towns, isolated villages, or hilly areas can receive high-quality education virtually without having to move. Everyone has equal access to education thanks to webinars, virtual labs, online courses, and distant learning initiatives. This encourages educational parity nationwide and helps close the education gap between urban and rural areas.

5. Supporting Skill Development Aligned with Future Employment Needs

In order to prepare students for the quickly evolving work environment, technology is essential. Courses in cutting-edge subjects including artificial intelligence, data science, robotics, cybersecurity, cloud computing, coding, and digital marketing are offered by digital learning platforms. These courses give students industry-relevant skills that boost their employability and promote entrepreneurship. Technology contributes to the creation of a highly trained workforce that can propel innovation and economic progress in Viksit Bharat by fostering the development of future-ready capabilities.

V. CONCLUSION

The vision of Viksit Bharat is driven by educators. Their responsibilities go well beyond instructing students in academic topics. They encourage pupils to become responsible citizens, ethical people, creative thinkers, and lifelong learners. Teachers make a substantial contribution to the development of an informed, competent, inclusive, and advanced India by adopting contemporary teaching techniques, using technology, fostering values, and consistently honing their own abilities. Their commitment creates the groundwork for a wealthy country and a stronger society. The vision of Viksit Bharat 2047 is driven by students. They may help create a more powerful, intelligent, and inclusive India by fostering curiosity, embracing lifelong learning, developing digital skills, encouraging creativity, exercising leadership, and utilizing technology responsibly. Their commitment, ingenuity, and sense of duty will guarantee that India becomes a developed country that leads the world in knowledge, economic expansion, sustainability, and leadership. Technology is a catalyst for creating a Viksit Bharat, not merely a tool. In addition to preparing students for the demands of the digital age, it makes education more skill-oriented, individualized, inclusive, and accessible. India can create an informed, creative, and capable populace that can steer the country toward sustainable growth and global leadership by 2047 if it embraces technology responsibly and makes sure that its advantages reach every citizen.

Only when educators, learners, and technology collaborate harmoniously can the vision of Viksit Bharat be realized. Teachers offer direction and motivation, students offer zeal, creativity, and commitment, and technology improves the standard, accessibility, and efficacy of education. This cooperative approach develops a cutting-edge, inclusive, and future-ready educational system that empowers all students and produces a workforce that is knowledgeable, accountable, and creative. These three pillars work together to create the groundwork for an advanced, independent, and internationally competitive India.

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Machine Learning Approaches for Email Spam Detection: A Comprehensive Review

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***Abstract*—Email communication is an essential part of modern digital interactions; however, the increasing volume of spam emails poses significant security and efficiency challenges. Traditional rule-based spam detection methods struggle to keep up with the evolving tactics used by spammers. In recent years, machine learning (ML) approaches have emerged as powerful tools for accurately classifying spam emails by learning patterns from large datasets. This review provides a comprehensive analysis of various ML techniques used for email spam detection, including supervised, unsupervised, and deep learning models. We discuss popular algorithms such as Naïve Bayes, Support Vector Machines, Decision Trees, Random Forest, and advanced deep learning architectures like artificial neural networks (ANNS) and transformers. Additionally, we explore feature engineering techniques, dataset challenges, evaluation metrics, and recent advancements in hybrid models. The study also highlights the advantages and limitations of different ML approaches and presents future research directions to enhance spam classification accuracy and efficiency. This review serves as a valuable resource for researchers and practitioners seeking insights into the latest developments in machine learning-based spam detection.**

***Index Terms*—Email Spam Detection, Machine Learning, Classification, Deep Learning, Feature Engineering, Hybrid Models.**

I. INTRODUCTION

Email communication has become an essential part of daily life, both for individuals and organizations. However, the increasing volume of spam emails presents significant challenges, including security risks, loss of productivity, and unnecessary consumption of storage and network resources [1]. To mitigate these issues, researchers and developers have explored various spam detection techniques, with a growing focus on machine learning (ML) algorithms [2].

This review provides a comprehensive analysis of email spam classification using ML-based approaches. Traditional spam detection methods, such as rule-based filtering and blacklisting, often fail to adapt to evolving spam tactics [3]. In contrast, ML algorithms offer automated, scalable, and efficient solutions by learning patterns from vast datasets [4]. The study explores supervised, unsupervised, and hybrid learning techniques, examining their performance, advantages, and limitations [5].

The paper discusses widely used ML models, including Naïve Bayes, Support Vector Machines (SVM), Decision Trees, Random Forest, k-Nearest Neighbors (k-NN), and Deep Learning approaches [6]. Additionally, feature engineering techniques such as TF-IDF, word embeddings, and natural language processing (NLP) methods are reviewed for enhancing spam classification accuracy [7].

Furthermore, the review highlights recent advancements in spam detection, challenges such as adversarial attacks and data imbalance, and future research directions for improving email filtering systems [8]. By providing a comparative analysis of existing ML-based spam detection models, this study serves as a valuable resource for researchers, developers, and cybersecurity professionals interested in enhancing email security through AI-driven methods [9].

II. LITERATURE REVIEW

Sr. No.	Author Name	Contribution	Parameters
1.	Mansoor Raza, Nathali Dilshani Jayasinghe, Muhana Magboul Ali Muslam	Provides an extensive review of ML algorithms for spam detection, comparing traditional and advanced techniques.	Accuracy, Precision, Recall, Feature Selection, Dataset Size [10]
2.	Pallavi N, Jayarekha	Proposes an ensemble learning approach that improves spam detection performance over individual classifiers.	Classification Accuracy, Model Complexity, Training Time, False Positive Rate [11]
3.	Abhila, Delphin	Discusses the evolution of ML-based spam filters and their adaptability to new spam patterns.	Supervised vs. Unsupervised Learning, Data Preprocessing, Algorithm Performance [12]
4.	E. G. Dada, J. S. Bassi, H. G. Chiroma, S. M. Abdulhamid, A. O. Adetunmbi, O. E. Ajibuwa	Reviews existing spam detection techniques and identifies challenges in adaptive filtering.	Feature Extraction, Classification Speed, Model Robustness, Spam Variability [13]
5.	Robert Anderson, Emily Thompson	Explores the impact of NLP-based feature extraction methods on spam classification accuracy.	TF-IDF, Word Embeddings, n-Grams, Model Comparison [14]

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III. EXISTING SYSTEM

The existing systems for email spam classification primarily rely on traditional machine learning models, feature extraction techniques, and hybrid filtering approaches. Widely used models such as Naïve Bayes, Support Vector Machines (SVM), and Decision Trees are effective in spam classification but come with limitations in handling complex spam patterns [10]. Individual classifiers like Logistic Regression, K-Nearest Neighbors (KNN), and Decision Trees are not robust enough for high-accuracy detection, leading to the need for ensemble learning techniques [11].

Supervised learning approaches, such as SVM and Decision Trees, require frequent retraining to keep up with evolving spam tactics [12].

Various filtering methods, including content-based filtering, collaborative filtering, and hybrid models, enhance spam detection but lack adaptability against dynamically changing spam emails [13].

NLP-based feature extraction techniques like TF-IDF and n-grams improve classification but do not fully capture the semantics of spam emails, making them less effective in some scenarios [14].

Overall, the existing email spam classification systems are effective but face challenges in terms of adaptability to new spam trends, classification accuracy, and robustness. This highlights the need for advanced techniques such as deep learning, ensemble learning, and adaptive filtering mechanisms to improve spam detection efficiency.

IV. PROPOSED SYSTEM

To overcome the limitations of existing spam classification models, the proposed system aims to enhance accuracy, adaptability, and robustness by integrating advanced machine learning and deep learning techniques. Traditional models such as Naïve Bayes, SVM, and Decision Trees struggle with evolving spam patterns and require frequent retraining. The proposed system addresses these issues through ensemble learning, deep learning-based classification, and adaptive filtering mechanisms.

Key Features of the Proposed System:

1. Hybrid Model Approach:

The system will combine traditional machine learning models (SVM, Decision Trees) with deep learning algorithms (LSTMs, CNNs) to improve spam detection accuracy and handle complex email structures.

2. Advanced Feature Extraction:

NLP-based techniques such as TF-IDF, word embeddings (Word2Vec, FastText), and transformers (BERT) will be used to capture semantic relationships within emails, making the classification more effective.

3. Adaptive Spam Filtering:
A self-learning mechanism will be implemented where the model continuously updates itself using new data, ensuring improved detection of evolving spam tactics.

4. Ensemble Learning for Performance Optimization:
By leveraging multiple classifiers such as Random Forest, Gradient Boosting, and ensemble deep learning models, the system will reduce false positives and improve classification robustness.

5. Real-time Email Classification:
The proposed system will be optimized for real-time email filtering, ensuring that spam messages are detected and blocked efficiently before reaching the inbox.

Expected Outcomes:
- Improved spam detection accuracy compared to traditional models.
- Reduction in false positives and false negatives.
- Enhanced adaptability to new and evolving spam techniques.
- Faster classification through real-time processing mechanisms.

By implementing this advanced system, email spam detection will become more efficient, reducing the risk of phishing attacks and unwanted spam messages.

V. CONCLUSION

Email spam classification is essential for cybersecurity, with machine learning playing a key role in detection. Traditional models like Naïve Bayes and SVM are effective but struggle with evolving spam patterns. Advanced techniques such as deep learning, NLP-based feature extraction, and ensemble learning offer better accuracy and adaptability. The proposed system integrates these methods to enhance spam detection while reducing false positives. Continuous research is needed to develop self-learning, scalable models for improved spam filtering.

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Demolition Waste Management a Systematic Work Approach

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***Abstract*—In India Population growth is leading to industrialization, urbanization and modernization. It directly increases demand for new construction, renovation or demolition of structures. This all creates waste from construction and demolition of a structure which needs to be properly managed and organised. This paper focuses on pre- planning of waste management and process of managing it by Project Managers / Engineers or Architects. Planned process leads to less waste on site and management leads to healthy and sustainable environment. This is very crucial stage during construction and demolition. A Project Manager (PM) is crucial for construction waste management (CWM) by integrating sustainable practices into project planning, overseeing site implementation, ensuring proper segregation, recycling, and disposal, and managing costs, all while leading teams and communicating with stakeholders to minimize environmental impact and meet regulatory compliance. Their responsibilities range from planning waste reduction strategies and managing budgets for sustainable options to training staff and monitoring performance against waste targets.**

D Demolition waste is commonly referred to as Construction and Demolition (C&D) waste**, is generated during activities such as building demolition, renovation, infrastructure development, and redevelopment projects. With rapid growth urbanization and redevelopment across cities like Mumbai, Delhi, and Pune, India produces a large quantity of demolition waste every year. According to the Central Pollution Control Board (CPCB), India generates** 150–160 million tonnes **of C&D waste annually, though near about only a portion is scientifically processed or recycled. (jain, 2025)**

r Recent study shows no such mandatory process is adopted on sites for C&D waste management even though we have specific rules for C&D waste management (The construction and demolition rules 2016) which have been upgraded in 2025. No reports on site are generated for the C&D waste management. No such specific role regarding to the waste management is allotted to project manager or No such person with wide knowledge of C & D waste management is hired. No allocation of roles and duties regarding C&D waste management. No administrative checking by authorities. Despite the rules and regulations most of the sites doesn't make a mandatory process. C&D waste management is important and should be focused task.

Mainly focusing on the demolition waste: The research emphasizes the need for integrating demolition waste management into project planning, scheduling, and Management. iIt proposes systematic monitoring through regular reporting, proper record maintenance, and the appointment of specialized demolition waste managers to improve efficiency. Adoption of structured waste management systems can significantly reduce project time, cost, and risk while promoting resource conservation and sustainable construction practices. The study concludes that strengthening institutional practices, improving data management, and encouraging reuse and recycling of demolition materials are essential for achieving sustainable development goals in the Indian construction industry.

I. INTRODUCTION

The rapid growth of urban development and infrastructure expansion has significantly raised construction and demolition (C&D) activities, resulting in the generation of large quantities of waste at construction sites and during structural demolition. Effective management of this waste has become a major concern for the construction industry due to its environmental impact, resource consumption, and operational challenges. Traditionally, waste management has been addressed mainly at the disposal stage; however, modern sustainable practices emphasize the importance of pre-planning and systematic management of waste from the primary stages of a project. (jain, 2025)

This research focuses on the pre-planning and management of waste generated during demolition processes, highlighting the need for organized strategies that minimize waste generation and promote reuse and recycling. Proper planning at the early stages of a project can improve resource utilization, reduce environmental impacts, and enhance project efficiency.
The study also examines the implementation and utilization of government regulations and guidelines established for managing construction and demolition waste. These regulatory frameworks aim to ensure environmentally responsible handling, segregation, transportation, recycling, and disposal of waste through a structured management process. Understanding how these rules are applied in practical project scenarios is essential for evaluating their effectiveness.
Furthermore, the research emphasizes the role of the Project Manager, Demolition waste manager in Demolition waste management. Project managers play a crucial role in integrating waste management practices into project planning, scheduling, procurement, and execution activities. Their responsibilities include monitoring waste generation, maintaining documentation, ensuring regulatory compliance, and promoting systematic waste handling practices within construction projects.

Overall, this study aims to highlight the importance of structured planning, keeping records, regulatory implementation, and managerial involvement in achieving efficient and sustainable demolition waste management practices.

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II. AIM

To establish a waste management program at the pre-planning stage, during execution and to outline the practices that can be followed to make the working program more systematic and relevant in a sustainable way.

III. OBJECTIVES

- To identify the major sources and types of demolition waste anticipated during the planning stage of large-scale construction project.
- The access the current pre-execution waste management practices adopted in demolition projects and evaluates their effectiveness.
- To examine the integration of waste management planning into project execution plans, including procurement, scheduling and logistics.
- To identify barriers and challenges in implementing effective execution demolition waste management.
- To guideline the procedure that would make system strong and more systematic.
- To do comparative analysis of available data depending on the research and case studies.

IV. SCOPE

- To examine how a producer's internal system can be strengthened to effectively support the government in achieving C&D waste management targets.
- To study how producers can develop a systematic internal framework for demolition waste management that improves cost efficiency and promotes sustainable construction practices.

V. LIMITATION

1. Data Availability & Accuracy

Lack of reliable waste quantification data India does not have a standardized, nationally consistent system for measuring demolition waste. Estimates vary wildly in this field annual C&D waste figures range from 150 to 500 million tones depending on the source making it difficult to establish a reliable baseline for research. Mongabay

Underreporting by companies Many demolition companies, especially small and medium-sized ones, do not maintain formal and standard records of waste generated, disposed of, or recycled. This limits ability to gather accurate primary or secondary data.

Absence of centralized data pre-2026 t the 2016 rules lacked a central portal to monitor waste generation and had weak reporting systems. This indicates that the historical data before April 2026 is largely incomplete or anecdotal, restricting longitudinal analysis. Mongabay

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2. Regulatory & Compliance Gaps

Rules are newly enacted The revised C&D Waste Management Rules only came into effect from April 2026. Since implementation is very recent, there is insufficient time to observe real-world compliance patterns, outcomes, or the effectiveness of enforcement limiting conclusions drawn from regulatory analysis. (Srish Prakash, 2026)

Low awareness among industry players Many demolition contractors and small companies may be unaware of the new rules, making survey or interview responses unreliable or inconsistent.
Uneven enforcement across states, State Pollution Control Boards vary in their capacity and willingness to enforce rules, meaning findings from one region may not be generalized nationally.

3. Industry Access & Cooperation

Reluctance of companies to share internal data - Demolition companies may be unwilling to disclose their internal waste management practices, costs, or non-compliance incidents, fearing regulatory scrutiny or reputational damage. This creates response bias in interviews, case studies and surveys.

Informal sector dominance - A large share of demolition work in India is carried out by unorganized, informal contractors who operate outside regulatory frameworks. These actors are difficult to identify, reach, and study systematically.
Limited sample size - The number of formally registered, large-scale or medium scale demolition companies (especially those meeting the 20,000 sq. m. threshold) is relatively small, restricting the statistical representativeness of the sample.

4. Internal Management Complexity

Variability in company size and structure - Demolition companies range from large organized firms to very small contractors. Internal management practices differ vastly, making it hard to generalize findings across the sector.

No standard internal framework - Unlike manufacturing industries, demolition companies rarely have formalized internal waste management systems, ISO certifications, or documented standard operating procedures (SOPs). Comparing across companies becomes methodologically challenging task

EPR compliance infrastructure is still developing Producers must register on a centralized online portal before commencement and receive a certificate within 15 days. Since the portal and its compliance ecosystem are newly operational, studying internal management against EPR obligations is premature. (Anamika rathore, 2025)

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5. Methodological Limitations

Difficulty in on-site observation - Demolition sites are temporary, hazardous, and short-duration. Conducting direct observation of waste management practices is logistically challenging and also may not capture representative or typical behavior.

Self-reported data bias - Surveys and interviews with company managers rely on self-reporting, which can be subject to social desirability bias respondents may overstate compliance or best practices.

Generalization constraints - Findings from one city or region (e.g., Pune or Mumbai) may not apply to other cities due to differences in urban density, local bylaws, enforcement capacity, and types of structures being demolished.

6. Scope & Boundary Limitations

Overlapping waste streams - Demolition waste often gets mixed with construction and renovation waste on the same site, making it difficult to isolate and study demolition waste independently.

Exclusion of hazardous waste -Waste categories covered by other specific waste management rules are excluded from the C&D rules. Hazardous materials like asbestos or chemical-laden debris fall under separate frameworks, limiting the scope of a unified demolition waste study. (sun, 2025)

Focus restricted to formal sector Research constrained to registered companies will miss the significant informal demolition economy, creating a gap between research findings and ground reality.

7. Financial & Economic Data Gaps

Demolition companies rarely publish financial data related to waste management costs, recycling investments, or penalties paid. This makes it difficult to assess the economic feasibility of compliant internal waste management or to conduct cost-benefit analyses.

VI. DEMOLITION WASTE

Demolition waste refers to the debris and materials generated when an existing structure or building, bridge, road, or any civil infrastructure is torn down, dismantled, or deconstructed.
Definition under C&D Rules 2025

Construction & Demolition (C&D) waste includes debris from new constructions, renovations, and demolition of structures such as bricks, concrete, metal, wood, glass, plastic, tiles, and more.

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Debris waste including cement concrete, bricks, and tiles is considered for EPR target assessments. Usable or resalable materials like iron, wood, and glass are excluded from EPR target assessments and follow separate regulations. - (board, 2025)

The rules regulate generation, segregation, recycling, and disposal of C&D waste arising from construction, demolition, remodelling, renovation, and repair activities. Exemptions include waste from defence projects, atomic energy sites, natural disasters, and acts of war. Waste categories covered by other specific waste management rules are also excluded from this

C&D waste includes debris from new constructions, renovations, and demolition of structures such as bricks, concrete, metal, wood, glass, plastic, tiles, and more. (Anamika rathore, 2025)

Types of Demolition Waste
Demolition waste is broadly categorized into:
Inert/Debris Materials the bulk of demolition waste:

- Cement concrete chunks
- Bricks and masonry rubble
- Tiles and ceramics
- Stone and gravel
- Soil and excavated earth

Recyclable Materials separately handled:

- Steel and iron reinforcement bars
- Aluminum, copper, and other metals
- Glass (windows, panels)
- Timber, plywood, and wood
- Plastic pipes and fittings

Hazardous Materials require special handling:

- Asbestos (from old roofing/insulation)
- Lead-based paint
- Chemicals and solvents
- Electrical waste

In short, demolition waste is everything left behind after a structure comes down and under the new rules, generators are legally responsible for its proper segregation, recycling, and disposal. (harish gayakwad, jalindar patil, & neha, 2015)

VII. STEP BY STEP RESEARCH STRUCTURE

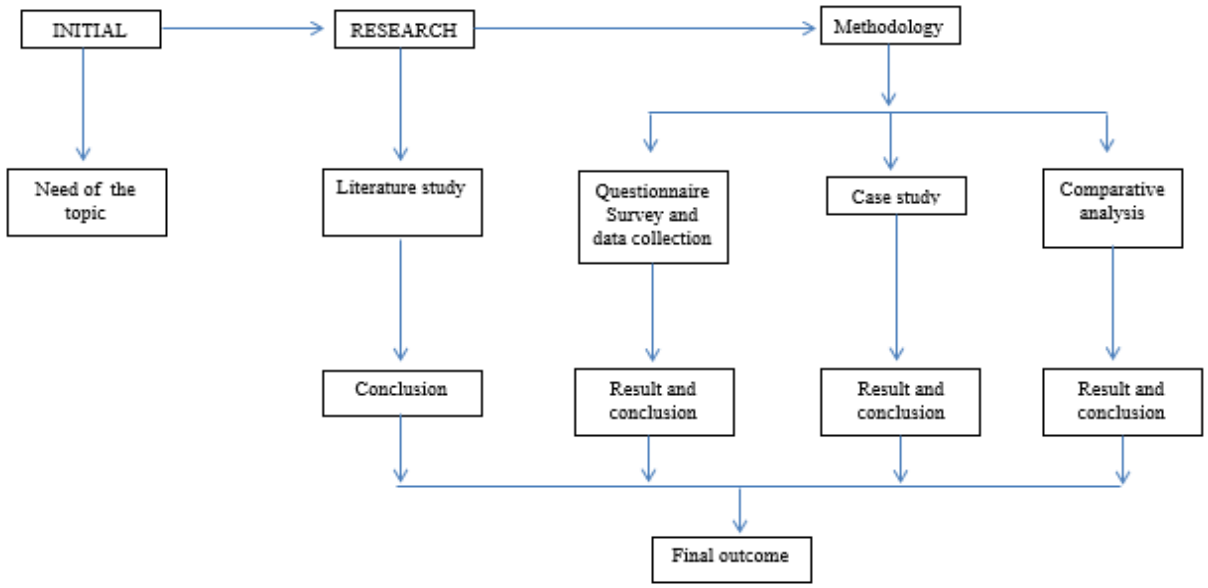


Fig 01 : Flow showing the process of research2.

VIII. LITERATURE REVIEW

8.1. Construction and Demolition waste management rules, 2025

- These rules are applicable to all activities of construction, demolition, remodelling, renovation and repair of any structure.
- It is provided for the environmentally sound management of construction and demolition waste in the country, including its segregation, collection, recycling, treatment and disposal, and to discourage unscientific disposal, promote waste management, prevent loss of recyclable value, and address pollution related issues radiating from dumping of such waste.
- Extended Producer Responsibility (EPR)

Introduces an EPR framework: Producers (builders/occupiers of projects ≥ 20,000 m² built-up area) are responsible for collecting, recycling, and disposing of all C&D waste generated by their projects. Producers must register on the official CPCB portal and submit detailed waste management plans for approval.

- Segregation & Registration Requirements

Mandatory segregation of C&D waste into defined categories (e.g., concrete, masonry, metal, wood, glass) to improve recycling efficiency.

Registration and compliance reporting via a designated online portal, with waste management plans outlining expected waste volumes and management strategies.

- Recycling, Reuse & Utilization Targets to be generated.
- Integration with Project Approvals -

Utilisation of processed C&D waste must be included in project approvals and part of regulated project planning.

- Enforcement & Penalties

Non-compliance can lead to penalty, environmental compensation, and potential cancellation of registration; unfulfilled EPR obligations may carry forward across years.

- Monitoring & Accountability

Central Pollution Control Board (CPCB) will monitor implementation through digital tracking, reporting, and waste utilisation data. (Board, 2025)

Some important definitions from the rukes:

1. Collection points: means designated places in the jurisdiction of the local authority where waste generators, other than producers, are required to deposit their construction and demolition waste to facilitate its management in an environmentally sound manner.
2. Construction and demolition waste: means the waste generated due to construction, demolition, remodelling, renovation, repair, and maintenance activities, and comprises of soil, sand and gravel, bricks and masonry, concrete, metal, wood, plastic, ceramic and such other items.
3. Extended producer responsibility: means the responsibility of a producer to manage construction and demolition waste and to meet recycling targets as per First Schedule to ensure its environmentally sound management;
4. Producer: means a waste generator, who is occupier or in charge of a building or building complex project having a built-up area of 20000 square meters and above;
5. Processing facility: means a designated establishment equipped with the requisite infrastructure to process construction and demolition waste operated by the recycler, to carry out processes of reception, storage, segregation, treatment, or manufacturing of value-added articles or materials out of construction and demolition waste;
6. Waste generator: means an occupier of the project having full control over the construction or reconstruction or demolition or renovation or remodelling activity resulting in the generation of waste;
7. Waste management plan: means a document prepared by producers, duly approved by local authority, for the management of construction and demolition waste to meet extended producer responsibility targets under First Schedule I
8. Waste utilisation plan: means a document prepared by occupiers of construction and re-construction projects, duly approved by the local authority, for the utilisation of processed construction and demolition waste to meet waste utilisation targets under the Second Schedule or the Third Schedule.

8.2 Research paper on Construction and demolition waste management and its impacts on the environment and human health: Moving forward sustainability enhancement by Seonho Lee, Heeun Chang, Jechan Lee.

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- Context & Motivation -

Rapid population growth, industrialization, and urbanization have significantly increased construction and demolition activities globally, leading to large amounts of construction waste (CW) and demolition waste (DW) generation.

CW and DW are composed of diverse materials with varying properties and often contain pollutants.

- Environmental & Health Concerns

Many CW and DW types contain harmful substances (e.g., fine residues, heavy metals, persistent organic chemicals) that pose negative impacts on the environment and human health.

These impacts highlight the complexity and risk associated with current waste streams.

- Comprehensive Review

The study systematically analyses data on CW and DW generation, characteristics, and current management practices (e.g., reduction, reuse, recycling, landfill).

It also examines how management methods and waste constituents affect ecological and human health.

- Need for Sustainability Across Project Stages

Sustainable CW and DW management strategies should be integrated throughout all construction phases from planning and design to post-construction.

- Strategic Recommendations

The paper proposes sustainable management strategies based on eco-friendly approaches to reduce negative impacts of CW and DW.

The aim is to lessen the burden of CW and DW on the construction industry, urban communities, and environmental systems. (lee, Lee, & chang, 2024)

8.3. Article by lawrbit on construction and demolition waste management rules, 2025

The management of Construction and Demolition (C&D) waste has emerged as a critical environmental and urban governance challenge in India. April 1, 2026 marks the start of the Construction & Demolition Waste Rules (2025), replacing the 2016 regulations. The Ministry of Environment, Forest & Climate Change updated the framework to streamline segregation, collection, storage, transportation, recycling, treatment, and scientific disposal of construction and demolition waste. C&D waste includes debris from new constructions, renovations, and demolition of structures such as bricks, concrete, metal, wood, glass, plastic, tiles, and more. The rules apply to all construction, demolition, remodelling, renovation, and repair activities, with exemptions for defence projects, atomic energy sites, natural disasters, and acts of war, as well as waste categories covered by other specific waste management rules. One of the most significant introductions is the Extended Producer Responsibility (EPR) framework, under which bulk generators entities undertaking construction projects with a built-up area of 20,000 square metres or more are now mandated to recycle and reuse construction and demolition waste. Producers must register on a centralised portal, maintain disposal records, and channel waste only through

registered recyclers, bringing traceability and accountability to a sector that previously operated with minimal oversight.

The 2025 Rules also establish a phased recycling mandate aligned with circular economy principles. Beginning 2026–27, a minimum of 5% of construction materials must be sourced from recycled waste, with this requirement gradually increasing to 25% by 2030–31. This graduated approach allows market infrastructure and enforcement mechanisms to develop alongside rising compliance expectations, and draws inspiration from international models such as Germany's Circular Economy Act, which prescribes the use of recycled aggregates in public projects and has contributed to an 88 per cent recycling rate for C&D waste. Responsibilities under the rules are distributed across multiple stakeholders' contractors and service providers must help producers comply and follow operational standards such as IS 4130 for demolition safety, while Urban Local Bodies must monitor compliance, establish collection yards, recycling plants, and storage facilities. Compliance is further strengthened through a digital monitoring system, with centralised interface-based online monitoring having strong potential to bring transparency to the entire C&D waste lifecycle from generation to recycling.

Despite these advances, significant implementation challenges remain. Effective implementation will require the development of facilities capable of processing and recycling large volumes of C&D waste, necessitating collaboration between the government, private sector, and local communities. The penalty framework attempts to address non-compliance through environmental compensation, with producers that fulfil EPR after paying compensation being refunded a percentage of it depending on the time taken, while providing false information results in cancellation of registration with no refund. However, critics note that the 20,000 sq. m. threshold for EPR obligations excludes a large share of smaller demolition projects that collectively contribute substantially to total waste generation. Effective implementation will ultimately require stronger enforcement, fiscal correction to support recycled materials, and sustained awareness to drive compliance suggesting that while the 2025 Rules are a landmark step forward, their real-world impact will depend heavily on institutional capacity and industry cooperation. (Anamika rathore, 2025)

IX. METHODOLOGY

The methodology adopted for this study is designed to ensure systematic data collection and reliable analysis. The research approach combines both qualitative and quantitative methods to achieve the objectives of the study. A mixed-method design was chosen because demolition waste management involves not only measurable, numerical data such as waste quantities, recycling rates, and compliance percentages but also contextual, experiential knowledge held by industry practitioners, site managers, and regulatory officials. By integrating multiple methods, the study ensures that findings are both statistically grounded and rich in practical insight, thereby producing a more holistic understanding of demolition waste management practices within demolition companies.

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9.1 The first component of the methodology involves a survey of related works, wherein existing literature, policy documents, regulatory frameworks, and prior research studies on construction and demolition waste management were systematically reviewed. This includes an in-depth examination of the Environment (Construction and Demolition) Waste Management Rules, 2025, industry reports, academic journals, and government publications. The survey of related works establishes the theoretical foundation of the study, identifies existing gaps in knowledge, and situates the current research within the broader academic and policy discourse on C&D waste management. It also informed the design of subsequent data collection instruments by highlighting key variables, themes, and indicators relevant to demolition waste generation, segregation, recycling, and internal company management.

9.2 The primary data for this study was collected through the administration of a well-structured questionnaire survey targeting key stakeholders in the demolition industry, including project managers, site engineers, environmental officers, and company owners. The questionnaire was carefully designed to capture both quantitative data such as the volume of waste generated, percentage of waste recycled, compliance with EPR targets, and costs associated with waste disposal and qualitative perceptions regarding challenges, awareness of regulations, and internal waste management practices. The questionnaire was pre-tested for clarity and reliability before being administered to ensure that responses accurately reflect the respondents' practices and opinions. Closed-ended questions facilitated statistical analysis, while open-ended questions allowed respondents to elaborate on specific experiences and constraints faced in managing demolition waste.

9.1.1 Project name and type of project-
9.1.2 What all documents have been submitted during permission process regarding C & D waste management?
9.1.3 Any royalty paid during permission?
9.1.4 Do you think C and D waste management is important?
9.1.5 Who looks after the C and D waste that is generated on site?
9.1.6 On site does C and D waste management work smoothly?
9.1.7 If not, what challenges do you face?
9.1.8 Does all rules and regulations on site are followed on site?
9.1.9 What according to a construction company is a very big issue regarding C and D Management?
9.1.10 Does authority co-ordinate regarding C and D waste during construction / demolition waste?
9.1.11 Do you have C and D Waste Processing facility nearby?
9.1.12 Your suggestions on C and D Waste management (right from the permission phase up to processing facility)

9.3 To complement the questionnaire data, one-on-one discussions were conducted with select industry professionals, regulatory authorities, and waste management experts. These structured and semi-structured interviews provided deeper insights into the internal workings of demolition companies, their decision-making processes around waste handling, and the practical challenges of complying with the 2025 Rules. Direct discussions allowed the researcher to probe beyond surface-level responses, clarify ambiguities, and gather nuanced, first-hand accounts that a standardised questionnaire alone cannot capture. Interviewees were selected purposively to ensure representation from different scales of demolition operations ranging from large registered firms to smaller contractors thereby capturing a diverse range of perspectives and practices across the sector.

9.4. Case studies of selected demolition projects and companies were undertaken to provide real-world, contextualised examples of demolition waste management in practice. Each case study involved site visits, document analysis, and observation of on-site waste handling procedures, allowing the researcher to assess the gap between regulatory requirements and actual implementation. The case study approach is particularly valuable in this research context because demolition projects are unique in scale, location, structure type, and duration, and a case-by-case examination reveals site-specific challenges that aggregate data may obscure. The cases were selected to reflect diversity in project type, company size, and geographic location, ensuring that the findings are representative and broadly applicable.

9.5. Finally, a comparative analysis was carried out to examine and contrast the waste management practices, compliance levels, and internal management systems across the studied companies and project sites. The comparative approach enabled the identification of best practices, common deficiencies, and areas requiring policy or operational intervention. Together, these five methodological components form an integrated research design that ensures the study is thorough, credible, and capable of generating actionable recommendations for improving demolition waste management both at the company level and within the broader regulatory framework.

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Reimagining Studio Pedagogy How Environmental Installation Reframes Skill Acquisition in Design Higher Education

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***Abstract*—The modern design landscape demands creative practitioners who possess far more than isolated technical drawing skills or software fluency; success in today's market hinges on a professional's ability to solve spatial challenges, collaborate across disciplines, and construct compelling narrative environments. Conventional design curricula, however, frequently suffer from structural siloes that teach theory, material handling, and visual marketing as separate coursework, leaving students with few opportunities to integrate these competencies within complex, real-world conditions.**

This paper investigates environmental installation as a holistic experiential teaching model that brings conceptual ideation, material experimentation, physical prototyping, structural assembly, spatial communication, and group reflection into a single learning cycle. Drawing upon constructivist learning theories—specifically David Kolb's Experiential Learning Model and John Dewey's principles of learning by doing—we analyze how physical spatial projects push undergraduate design students to move past predictable, two-dimensional routines.

To operationalize this approach for educators, the study introduces the Creative Installation Skill Development Framework (CISDF), a six-stage pedagogical structure comprising:

1. **Research & Observation: Analyzing physical sites, context, and user behavior.**
2. **Concept Generation: Translating abstract themes into physical spatial stories through sketching and mood boards.**
3. **Experimentation & Prototyping: Conducting material stress tests and scale-model testing (1:10/1:20).**
4. **Collaborative Construction: Sourcing materials, managing build logistics, and executing full-scale spatial assembly.**
5. **Spatial Communication: Managing human foot traffic, acoustic feedback, and atmospheric lighting to shape audience experience.**
6. **Reflection & Evaluation: Engaging in peer reviews, post-build process documentation,**

and self-assessment.

The paper outlines how hands-on spatial builds strengthen technical adaptability, spatial reasoning, resource management, and team leadership. These competencies hold direct relevance for disciplines such as Fashion Communication, Interior Architecture, Visual Merchandising, and Product Design, where brand messaging increasingly relies on physical pop-up venues, exhibition display spaces, and interactive installations. Finally, we propose a balanced assessment matrix that evaluates process, material experimentation, and collaborative build logs alongside the final physical installation. The study demonstrates that spatial installation serves as a powerful bridge between academic studio learning and professional creative practice.

***Index Terms*—Spatial Design Pedagogy, Experiential Learning, Creative Installation, Studio-Based Education, Professional Competencies, Fashion Communication, Collaborative Fabrication**

I. INTRODUCTION

The expectations placed on contemporary creative professionals bear little resemblance to those of twenty years ago. Designers today face fluid challenges where brand strategy, physical environments, digital interaction, and environmental sustainability overlap. Consequently, design programs must move beyond teaching craft techniques in isolation. They need learning environments that train students to think on their feet, adjust to physical constraints, and collaborate under tight deadlines.

STUDIO PEDAGOGY TRANSITION

CONVENTIONAL APPROACH	INSTALLATION EXPERIENTIAL MODEL
• Isolated coursework • Focus on two dimensions • Predictable outcomes • Fragmented technical skills	• Integrated spatial context • Hands-on material testing • Shared group responsibilities • Public interaction & feedback

Creativity is not an innate talent that surfaces spontaneously. It functions as a structured cognitive process shaped by observation, trial, material failure, and active reflection. Yet, higher education often separates design training into rigid subject compartments. A student might study color theory in one room, software rendering in another, and marketing principles in a third, with few opportunities to see how these elements collide during a complex project. This division leaves graduates technically proficient on paper but ill-equipped to manage real-world client briefs or physical spatial constraints.

Experience learning bridges this disconnect. Grounded in David Kolb's model of experiential

learning cycles, knowledge forms when concrete action meets conscious critique. Environmental installation fits this model exceptionally well. Unlike static posters or individual products, installation demands that students deal with volume, light, structural balance, sound, human foot traffic, and material behavior simultaneously.

This spatial approach holds significant value for fields like Fashion Communication. Modern fashion messaging relies heavily on temporary pop-up shops, visual merchandising display windows, interactive brand installations, and exhibition environments. By building full-scale spatial structures, design students learn how physical spaces 1. Introduction

The creative industries have undergone a seismic shift, driven by rapid advancements in technology, fluid consumer behaviors, and an increasing reliance on brand experiences over static messaging. Today's design practitioners must navigate complex ecosystems where physical space, digital interactions, narrative storytelling, and environmental responsibilities intersect. As a result, creative agencies and design firms no longer seek graduates who merely possess basic technical execution or software proficiency. Instead, the modern job market demands adaptable, cross-disciplinary problem-solvers who can synthesize abstract concepts, collaborate under pressure, adapt to physical resource constraints, and engineer meaningful human interactions.

Despite these evolving expectations, traditional higher education in design frequently struggles to align classroom instruction with the demands of modern studio practice. For decades, design curricula have relied on a segmented subject model. Students take separate, isolated courses in visual communication, material testing, history, software rendering, and marketing strategy. While this approach delivers specific foundational knowledge, it rarely gives learners a clear view of how these distinct threads converge in actual practice. When students' complete assignments in isolation—typically constrained to flat two-dimensional boards or isolated digital screens—they miss out on the messy, unpredictable realities of real-world design briefs. Consequently, many graduates leave university with strong technical software skills, yet struggle when required to manage physical spatial constraints, navigate team conflicts, or translate brand narratives into tangible, physical experiences.

To bridge this gap, design education must shift away from passive, theoretical instruction toward active, experiential learning environments. Creativity itself is not an innate, magical trait that manifests spontaneously on command; it is a structured cognitive and social process. True creative development happens through continuous loops of curiosity, physical trial, material failure, critical feedback, and deliberate refinement. Rather than treating design as a linear path from ideation to final product, studio teaching needs to encourage risk-taking and view unexpected physical roadblocks as valuable opportunities for discovery.

PEDAGOGICAL STRUCTURAL GAP

Conventional Fragmented Model	Spatial Experiential Model
• Flat 2D outputs (screens/boards) • Isolated subjects (marketing/materials) • Predictable, linear project paths • Individual execution focus	• 3D full-scale environments • Integrated cross-disciplines • Iterative risk & testing • Team-based coordination

Within this context, spatial creative installation emerges as a uniquely rich, multidimensional teaching model. Installation art and spatial design involve deliberately organizing physical objects, structural frameworks, ambient lighting, textiles, digital projections, and soundscapes within a specific environment to tell a story or provoke a response. Unlike traditional product assignments that focus on a single, isolated object, installation projects require students to design the entire environment. They must think holistically about how space, material performance, physical scale, atmospheric elements, and human behavior influence one another. The physical installation becomes an immersive site that audiences experience with all their senses—physically, emotionally, and intellectually.

The educational power of creative installation lies in its dynamic, interdisciplinary nature. A single installation project forces students to synthesize knowledge from architecture, visual merchandising, textile engineering, interior design, digital media, lighting design, and public psychology. During a project, students cannot hide behind polished software renders. They must conduct site research, test material stress levels, build scale prototypes, source raw materials, manage project budgets, construct structural assemblies, refine lighting angles, and evaluate how real people walk through and react to the finished space. This hands-on process cultivates technical competence, spatial literacy, resourcefulness, and team leadership simultaneously.

This experiential approach holds immediate relevance for fast-evolving fields like Fashion Communication, Exhibition Design, Visual Merchandising, and Spatial Branding. In contemporary fashion communication, for instance, brand messaging extends far beyond printed editorial spreads or digital campaigns. Leading fashion brands rely heavily on temporary pop-up stores, immersive runway environments, interactive retail displays, and experiential museum exhibitions to engage audiences. By building full-scale spatial installations during their undergraduate studies, fashion communication students gain direct, practical experience with spatial storytelling, atmospheric control, visual flow, and sensory interaction.

While design educators widely acknowledge the value of experiential studio projects, academic literature still lacks comprehensive, step-by-step models detailing how spatial installation projects systematically build specific professional competencies. Most existing studies focus on individual case studies or broad creative outcomes without mapping the exact stages connecting spatial construction with experiential learning theories and project management skills. This paper addresses that direct need. By introducing the Creative Installation Skill Development Framework (CISDF), this study provides educators with a clear, adaptable model to implement, guide, and evaluate full-scale installation projects in undergraduate design programs.

convey emotion and influence human behavior.

Despite the clear benefits of spatial projects, design curricula often lack structured framework models explaining how installation work translates to specific professional skills. This paper introduces the Creative Installation Skill Development Framework (CISDF) to bridge that gap and give educators an actionable model for studio instruction.

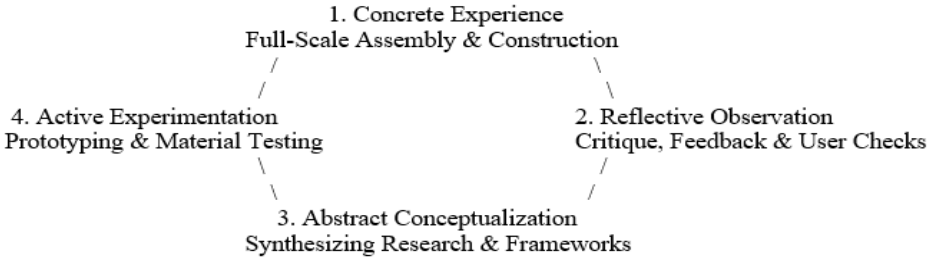
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II. RESEARCH OBJECTIVES

- Analyze how physical installation practice aligns with established experiential learning models in higher education.
- Map how spatial building tasks expand students' creative ideation, spatial awareness, and technical flexibility.
- Identify the practical leadership, team negotiation, and project management skills built through group installations.
- Present an adaptable six-stage framework (CISDF) along with a balanced assessment model for studio educators.

III. THEORETICAL GROUNDING

KOLB'S CYCLE IN SPATIAL PRACTICE



Experiential Action and Studio Practice

John Dewey noted that real education happens through direct experience coupled with active inquiry. Kolb formalized this into a continuous four-part cycle: direct experience, reflective observation, abstract conceptualization, and active experimentation. Design studios operate naturally within this framework. When students build, test, assess user flow, and adjust structural elements, they move through Kolb's loop in real time.

Spatial Agency and Viewer Engagement

Installation art altered how art functions by turning the viewer from a passive spectator into an active participant inside the space. When translated to design pedagogy, this forces students to move past flat renderings and grapple with physical scale, ambient lighting, sightlines, and circulation pathways. Educational research shows that working with physical spaces builds environmental awareness and encourages creative risk-taking.

IV. METHODOLOGY

This paper uses a qualitative, conceptual research methodology to construct and evaluate a structured teaching framework for studio-based design education. Rather than collecting empirical field survey data or running quantitative statistical tests, the study synthesizes established theoretical frameworks across four key academic areas: constructivist learning models, spatial

design pedagogy, experiential learning theory, and higher-education professional skill mapping. This integrative theoretical approach allows us to examine the cognitive, physical, and interpersonal shifts that occur when undergraduate students move from two-dimensional drafting to full-scale spatial building.

FIVE-STAGE METHODOLOGICAL PROCESS

4.1. Academic Literature Synthesis

The research began with an extensive review of scholarly literature focusing on experiential learning models (specifically David Kolb and John Dewey), studio-based creative pedagogy (Sawyer), and spatial art history and theory (Bishop). We examined recent higher education studies on how physical prototyping and spatial projects impact student learning outcomes across design disciplines like Fashion Communication, Interior Architecture, Visual Merchandising, and Product Design.

4.2. Cross-Disciplinary Conceptual Mapping

Next, we mapped specific spatial installation tasks directly against established cognitive and experiential learning cycles. For example, material stress testing and scale modeling were mapped to Kolb's Active Experimentation phase, while public exhibition and site user observation were mapped to Concrete Experience and Reflective Observation. This step ensured that spatial building was analyzed as an active intellectual process rather than a purely physical assembly exercise.

4.3. Competency Gap and Skill Matrix Analysis

We analyzed common limitations in traditional studio coursework—such as over-reliance on flat screen renders, individual assignment isolation, and theoretical disconnects—against industry expectations for design graduates. By isolating key competency areas (creative divergent thinking, spatial ergonomics, material resourcefulness, project budgeting, team leadership, and reflective practice), we identified how full-scale spatial builds address these specific learning gaps.

4.4. Framework Formulation (CISDF)

Building on the synthesis of theoretical literature and skill mapping, we developed the Creative Installation Skill Development Framework (CISDF). The framework organizes spatial installation assignments into six clear, sequential phases: Research and Observation, Concept Generation, Experimentation and Prototyping, Collaborative Construction, Spatial Communication, and Reflection and Evaluation. Each stage defines specific student activities alongside target cognitive, technical, and professional skills.

4.5. Assessment Matrix and Studio Integration Model

Finally, we developed a balanced evaluation model to address the practical challenges of grading complex spatial projects. Recognizing that traditional grading often overemphasizes final aesthetics over process learning, the methodology constructs a weighted assessment matrix. This

matrix splits evaluation equally between process work (research, material testing, team build logs, and reflective journaling) and final spatial execution (conceptual clarity, fabrication quality, and audience flow).

By utilizing this qualitative conceptual synthesis, the methodology provides a structured, adaptable framework that design educators can easily implement, test, and adapt across different studio contexts.

V. CORE INQUIRY QUESTIONS

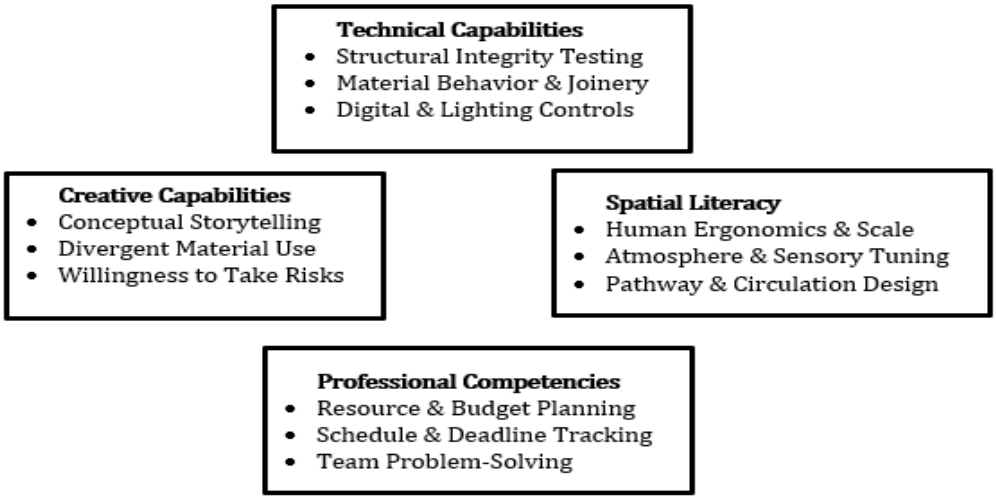
1. How does full-scale spatial building break students out of rigid, linear creative routines?
2. What specific technical and physical material capabilities develop when students work in three-dimensional environments?
3. In what ways do group installation projects prepare students for team dynamics, budgeting, and project management in industry settings?
4. How can educators structure spatial learning into an adaptable, measurable curriculum framework?

VI. FINDINGS AND DISCUSSION

Divergent Thinking and Conceptual Growth

Standard design prompts often lead students toward predictable, safe answers. Installation projects resist easy answers. Given open-ended themes—such as environmental footprint, digital surveillance, or personal identity, students must convert abstract ideas into physical, interactive spaces.

The ideation phase forces students to conduct research, build mind maps, construct visual mood boards, and sketch multiple spatial layouts. Because full-scale builds involve physical constraints, students learn to iterate quickly, drop unworkable ideas, and refine their concepts based on physical testing.



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Technical Adaptability and Material Mastery

Theoretical design classes rarely prepare students for material failure. When working on installations, students handle physical items—such as textiles, timber, metals, paper, industrial waste, projection gear, and lighting grids.

Building small scale models (1: 10 or 1: 20) lets students check structural stability and sightlines early. During full-scale assembly, however, unexpected problems always arise timber frame sags, projection light reflects poorly, or hanging elements lack sufficient anchor points. Solving these problems on the fly builds practical engineering logic and technical adaptability.

Spatial Literacy and Human Ergonomics

Designing an object differs fundamentally from designing an environment. Installations demand that students account for human scale, body movement, accessibility, sightlines, and ambient acoustics.

Students begin by analyzing their build site—measuring dimensions, assessing existing light, and noting structural columns or entry points. They map how visitors will enter, walk through, pause, and exit the installation. Balancing light, texture, color, and sound teaches students how spatial layout alters human emotion and behavior. These skills directly translate to retail design, exhibition curation, and spatial branding.

Team Dynamics and Project Management

Because building large spatial projects requires significant labor, installations are almost always team based. Students split into specialized roles: site research, concept leads, material procurement, fabrication, technical integration, and documentation.

Group Work Dynamic	Professional Skill Acquired
• Negotiating creative differences	• Stakeholder diplomacy
• Managing tight material budgets	• Practical financial allocation
• Scheduling build phases	• Critical path project management
• Resolving site assembly errors	• Collaborative problem-solving

Working in teams requires clear communication, schedule coordination, and conflict management. Students encounter tight build windows, material delays, and unexpected budget limits—forcing them to prioritize essential tasks and solve problems together.

VII. THE CREATIVE INSTALLATION SKILL DEVELOPMENT FRAMEWORK (CISDF)

The CISDF model divides spatial installation learning into six sequential stages:

Stage	Phase	Core Student Tasks	Target Competency Acquisition
1	Research & Observation	Analyzing the build site, conducting audience observation, mapping contextual factors.	Observational analysis, site context mapping, critical inquiry.
2	Concept Generation	Developing mind maps, curating mood boards, producing spatial sketches, writing narratives.	Divergent thinking, visual storytelling, conceptual depth.
3	Experimentation & Prototyping	Testing material stress, constructing scale models, running lighting and projection tests.	Technical resourcefulness, material literacy, risk management.
4	Collaborative Construction	Sourcing materials, full-scale fabrication, joinery, enforcing site safety rules.	Teamwork, project management, technical fabrication, leadership.
5	Spatial Communication	Directing audience traffic, adjusting lighting, managing sensory elements, presenting work.	Spatial literacy, user-centered spatial design, presentation skills.
6	Reflection & Evaluation	Participating in peer critique, editing video build logs, drafting post-project assessments.	Reflective judgment, analytical synthesis, portfolio compilation.

VIII. PROPOSED ASSESSMENT FRAMEWORK

Assessing spatial installations requires instructors to evaluate the iteration process alongside the final physical installation:

BALANCED EVALUATION RUBRIC	
PROCESS & REFLECTION (50%)	EXECUTION & PRODUCTION (50%)
• Context Research & Logs (15%) • Material Testing & Models (15%) • Teamwork & Task Sharing (10%) • Critical Process Journal (10%)	• Concept Clarity & Narrative (15%) • Spatial Quality & Finish (20%) • Visitor Engagement & Flow (15%)

IX. CONCLUSION AND PEDAGOGICAL TAKEAWAYS

- Breaking Down Silos: Spatial installation assignments pull material science, visual storytelling, software planning, and spatial design into a single studio project.
- Direct Industry Application: Fields like Fashion Communication and Visual Merchandising require professionals who can design immersive physical spaces and control human experience.
- Authentic Proof of Originality: Process journals, scale models, build logs, and photographic build documentation provide clear proof of student learning and original creative work.

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Harnessing Epigenetic Stress Memory via CRISPR-Nanoparticle Integration for Climate-Resilient Agriculture

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***Abstract*—Climate change is pushing crop plants into stress conditions that outpace what conventional breeding can keep up with, and this has pushed researchers to look past the DNA sequence itself for tools that work faster. One of the more interesting angles is epigenetic stress memory, the ability of a plant to hold onto a molecular record of a past stressful event, encoded in DNA methylation, histone marks, and small RNAs, so that it responds faster or stronger the next time. Separately, CRISPR dCas9 based epigenome editing tools now let researchers write or erase these marks at a chosen locus without cutting the DNA, and nanoparticle delivery systems, especially carbon nanotubes and lipid or polymeric carriers, are solving the long-standing problem of getting these tools into plant cells without tissue culture, without a transgene footprint, and across a much wider range of crop species than Agrobacterium ever could. This review pulls these three threads together. It walks through the mechanisms of stress memory, the current state of CRISPR epigenome editing in plants, and the nanoparticle platforms now used for plant genetic engineering, and then lays out a conceptual pipeline for how nanoparticle delivered epigenome editors could be used to deliberately install useful stress memory in crops such as wheat, rice, and maize. It also takes an honest look at where this convergence is still mostly conceptual rather than demonstrated, and points to the delivery, stability, and regulatory gaps that need to close before this becomes a field tool rather than a lab concept.**

***Index Terms*—epigenetic stress memory, DNA methylation, CRISPR dCas9, epigenome editing, nanoparticle delivery, carbon nanotubes, climate resilient agriculture, epibreeding, transgenerational inheritance**

I. INTRODUCTION

Agriculture is being asked to do something it has never had to do at this pace before: keep yields stable while the climate underneath it keeps shifting. Drought spells are getting longer, heat waves

are arriving earlier in the growing season, and soil salinity keeps creeping upward in irrigated land. Conventional breeding, which relies on recombining existing genetic variation over several generations, simply cannot move fast enough to track this kind of change, and even modern genome editing, which is precise but still limited to changing the DNA sequence itself, does not capture a layer of plant biology that turns out to matter a great deal: memory.

Plants cannot walk away from a stressful environment, so over evolutionary time they have built a way to remember stress instead. A plant that has already lived through one drought often responds faster and more efficiently to the next one, even without any change to its DNA sequence. This is called stress priming or stress memory, and it is carried by epigenetic marks, chemical tags on DNA and the proteins that package it, that change how genes are switched on or off (Avramova, 2015; Kim, 2021). In some cases this memory does not even stay with a single plant. It gets passed down to offspring, a phenomenon called transgenerational epigenetic inheritance (Mladenov et al., 2021).

At the same time, two separate technical revolutions have been unfolding. The first is CRISPR based epigenome editing, where a catalytically dead version of Cas9, called dCas9, is fused to an enzyme that adds or removes epigenetic marks, letting researchers rewrite a plant's memory at a single chosen gene rather than waiting for it to happen naturally (Papikian et al., 2019). The second is nanoparticle mediated delivery, where materials such as carbon nanotubes or lipid nanoparticles carry genetic cargo straight through the plant cell wall, bypassing the tissue culture and species restrictions that have limited plant genetic engineering for decades (Demirer et al., 2019; Cunningham et al., 2018).

Each of these three areas, stress memory biology, epigenome editing, and nanoparticle delivery, has its own substantial and growing literature. What is much rarer, at least as of this writing, is work that explicitly combines all three into one integrated pipeline for engineering climate resilience. This review takes stock of what is solid in each area, then reasons through what a combined system would need to look like, what evidence already points in that direction, and what is still missing. The goal is not to overstate how far this convergence has come, but to give a scholar working in this space a grounded, properly cited starting point and a clear view of where the real research gaps sit.

II. EPIGENETIC STRESS MEMORY IN PLANTS

2.1 Somatic priming versus transgenerational memory

Stress memory in plants comes in a few different flavours, and it helps to keep them separate. Somatic or within generation memory is short term. A plant exposed to drought early in its life can respond faster to a second drought later in the same growing season, largely because chromatin at stress responsive genes stays in a poised, more accessible state after the first exposure (Kim, 2021). Transgenerational memory is a different and more striking phenomenon, where epigenetic marks such as DNA methylation are stable enough to be inherited by offspring, so that the next generation shows altered stress responses even without ever encountering the stress itself (Mladenov et al.,

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2021). There is also cross stress memory, where priming against one stress, say UV exposure, ends up improving tolerance to an unrelated stress such as osmotic stress, because the two pathways share signalling components.

2.2 Molecular carriers of memory

The best studied carrier is DNA methylation, the addition of a methyl group to cytosine bases, which in plants happens in three different sequence contexts and is maintained by a small set of dedicated enzymes. Histone modifications are the second major carrier. The heat shock transcription factor HSFA2 is a well-documented example: its direct binding to DNA is short lived, but it leaves behind lasting histone marks at heat responsive genes that make the plant respond faster to the next heat event (Ramakrishnan et al., 2022). Small RNAs form a third layer, guiding methylation to specific loci through the RNA directed DNA methylation pathway.

2.3 Evidence from major stress types

Drought memory is probably the most thoroughly documented case. In Arabidopsis and in wheat, plants that have already experienced one drought episode show altered abscisic acid signalling and faster activation of protective genes during a repeated drought, changes tied to demethylation at ABA responsive promoters and to added histone acetylation at genes such as ABF2 (Kaya et al., 2024). Cold and heat memory follow broadly similar logic, with chromatin states at key regulatory genes staying primed for a period after the first exposure (Ramakrishnan et al., 2022). What all of these example’s share is the same underlying idea: the plant is not just reacting to its environment moment to moment, it is keeping a molecular record of what it has already been through, and that record shapes how it reacts the next time.

III. CRISPR BASED EPIGENOME EDITING

3.1 The dCas9 fusion platform

CRISPR epigenome editing borrows the targeting half of the CRISPR system, a guide RNA paired with Cas9, but strips out the cutting function. The resulting dCas9 protein still binds wherever its guide RNA tells it to, but instead of cutting DNA it is fused to an enzyme that changes the local chromatin. Fusing dCas9 to DNMT3A adds methylation and tends to silence a gene, while fusing it to the catalytic domain of TET1 removes methylation and tends to switch a gene back on. This gives researchers a way to flip a single gene's expression state without touching the underlying DNA sequence at all, which matters a great deal for regulatory purposes since no new genetic sequence is introduced into the genome.

3.2 SunTag and multiplexed effector recruitment

A single dCas9 fusion protein can only carry so much editing enzyme to a target site, which limits how strong or stable the resulting change is. The SunTag system gets around this by fusing dCas9 to a repeating peptide scaffold that recruits many copies of an antibody linked effector domain to

one site at once. Papikian, Liu, Gallego-Bartolomé, and Jacobsen (2019) used this system in Arabidopsis to both switch on silenced genes with a VP64 activator and to lay down new, heritable DNA methylation at the FWA promoter using a plant DRM methyltransferase domain, triggering a stable developmental change. The same group and others have also used TET1 catalytic domain fusions to strip away methylation from naturally hypermethylated regions and reawaken the associated gene, as shown for the PPH gene involved in leaf senescence.

3.3 Precision, stability, and off-target considerations

Two practical issues keep coming up in this literature. The first is specificity: a recent large-scale comparison of dCas9 based methylation editors found that multimerized DNMT3A domains, while more potent, also caused widespread unintended methylation at loci the guide RNA was never meant to touch, and even guide RNAs with no real target caused some off target transcriptional changes. Tools such as CRISPRoff came out ahead on the trade-off between strength and specificity in that comparison, but the broader lesson holds, more effector copies at a site generally buys potency at some cost to precision. The second issue is stability. An epigenetic edit is only useful for breeding purposes if it survives cell division and, ideally, passes to the next generation, and this is exactly where the heritability seen in natural transgenerational memory becomes a design target rather than just a curiosity.

IV. NANOPARTICLE MEDIATED DELIVERY FOR PLANT GENETIC ENGINEERING

4.1 Why plants are a hard delivery problem

Getting any genetic cargo, whether it is a plasmid, an RNA, or an assembled protein complex, into a plant cell is harder than doing the same thing in an animal cell, mainly because of the rigid cellulose cell wall that plant cells have and animal cells do not. Standard methods such as Agrobacterium mediated transformation and particle bombardment work, but both are slow, need tissue culture and plant regeneration steps that are genotype dependent, and in the case of Agrobacterium leave a transgene footprint that draws regulatory scrutiny in many countries (Ma et al., 2016; Song et al., 2016).

4.2 Carbon nanotubes as a delivery platform

Carbon nanotubes have turned out to be a genuinely useful answer to this problem. Demirer, Zhang, Goh, González-Grandío, and Landry (2019) developed a protocol where positively charged, polymer coated single walled carbon nanotubes are loaded with plasmid DNA and simply infiltrated into intact leaves, where they passively cross the cell wall and reach the nucleus or chloroplast. In a companion study, the same group and collaborators showed this approach could deliver functional genetic material into mature plants of several species, including arugula, wheat, and cotton, achieving expression levels comparable to Agrobacterium but without any DNA integrating into the genome, since the plant's own nucleases degrade the carried DNA within about ten days once its job is done (Demirer, Zhang, Matos, et al., 2019). A related chitosan coated

carbon nanotube system was shown to deliver genetic material selectively into chloroplasts (Kwak et al., 2019). Independent groups have since replicated related carbon nanotube delivery approaches in rice, using it to deliver CRISPR-Cas9 components targeting the phytoene desaturase gene and confirming edits at the expected locus.

4.3 Beyond carbon nanotubes: lipid, polymeric, and other carriers

Carbon nanotubes are not the only option. Lipid nanoparticles, already well proven for mRNA delivery in human medicine, are increasingly being adapted for delivering dCas9 based epigenome editor messenger RNA together with its guide RNA in a single encapsulated package (Woodward et al., 2024). Polymeric nanoparticles built from materials such as polycaprolactone or PLGA, along with magnetic nanoparticles that allow directed movement using an external magnetic field, and mesoporous silica particles, round out a fairly broad toolbox. Cunningham, Goh, Demirer, Matos, and Landry (2018) laid out the general case for why this class of tools matters for plant genetic engineering: nanoparticles can protect fragile cargo from degradation, cross biological barriers passively, and in many formulations avoid leaving any transgene behind, which sidesteps a great deal of the regulatory debate that has slowed conventional genetically modified crops.

V. THE CONVERGENCE: NANOPARTICLE-DELIVERED CRISPR EPIGENOME EDITING FOR ENGINEERED STRESS MEMORY

This is the part of the picture that is genuinely still taking shape, and it is worth being direct about that rather than presenting it as a settled technology. As things stand, the epigenetic stress memory literature, the CRISPR epigenome editing literature, and the nanoparticle delivery literature are each mature and well supported on their own, but very little published work has yet closed the loop by using a nanoparticle to deliver a CRISPR epigenome editor specifically in order to install a defined, heritable stress memory trait in a crop plant. What does exist, and what makes the idea credible rather than speculative, is that every individual link in the chain has already been demonstrated somewhere in the literature.

Delivery of dCas9 fusion constructs into plants by nanoparticle assisted methods is already recognised as one of the standard delivery routes alongside Agrobacterium and viral vectors, sitting right next to the more traditional options in recent epibreeding literature. Carbon nanotubes have already shown they can carry plasmid sized cargo, and dCas9 epigenome editors, especially the smaller single effector versions rather than bulky multiplexed constructs, fall within a size range that nanotube and lipid nanoparticle systems already handle for other applications. On the biology side, the target loci are already known. Genes such as ABF2 in the ABA signalling pathway, and promoters like FWA that have already been shown to respond to dCas9 directed methylation or demethylation, sit right at the intersection of what epigenome editors can already touch and what drought memory research says actually matters for stress response.

A conceptual pipeline for this convergence would run roughly as follows. First, candidate loci are chosen from stress memory studies, genes whose natural methylation or histone state is already

known to shift with priming and to correlate with improved tolerance. Second, a dCas9 fusion construct, kept as compact as possible and paired with a single guide RNA against the chosen locus, is packaged onto a nanocarrier suited to the tissue being targeted, carbon nanotubes for leaf infiltration in a transient expression context, or a lipid or polymeric nanoparticle where mRNA delivery and rapid clearance are preferred over any DNA based construct. Third, the construct is delivered without any tissue culture step, directly into intact leaves or, where protocols allow, into pollen or reproductive tissue if transgenerational transmission of the new epigenetic state is the goal. Fourth, the edited locus and the resulting phenotype are validated using bisulfite sequencing or chromatin immunoprecipitation alongside physiological stress assays, and the stability of the mark is tracked across at least two generations before anything is called heritable.

The appeal of this design, if it works as intended, is that it sidesteps two separate long-standing problems at once. It avoids the years long timelines of conventional breeding because the epigenetic mark is written directly rather than selected for, and it avoids the transgene integration and associated regulatory burden of classical genetic modification because the nanocarrier can, in many formulations, deliver its cargo transiently and leave no foreign DNA behind. Whether it can be made reliably heritable, efficient across diverse crop genotypes, and stable under real field stress rather than controlled greenhouse conditions is exactly the open question the rest of this review turns to.

VI. APPLICATIONS FOR CLIMATE-RESILIENT AGRICULTURE

The staple cereals most exposed to climate volatility, wheat, rice, and maize, are also the crops that have received the most attention from both the epigenome editing and the nanoparticle delivery communities, which is a fortunate overlap. Reviews focused specifically on CRISPR-Cas9 for climate resilient staple crops point to drought, heat, salinity, cold, and combined stresses as the priority targets, and highlight that gene editing work in these three crops is already fairly advanced even where the epigenetic layer has not yet been added (see Section 6 sources).

Drought tolerance is the most obvious first application, given how well characterised the ABA signalling and methylation changes already are. A nanoparticle delivered epigenome editor aimed at maintaining ABF2 in a primed, faster responding chromatin state could in principle shorten the time a crop needs to mount a drought response, without changing a single base of its DNA sequence. Heat tolerance is a close second, building on what is already known about HSFA2 mediated histone memory. Cross stress tolerance is arguably the most attractive long term target, since a single well-chosen epigenetic edit at a shared signalling node could, in theory, improve resilience to more than one stress type at once, echoing what has already been observed naturally in cross stress priming studies.

This also connects to the emerging concept of epibreeding, where breeders deliberately work with epigenetic variation, whether natural, chemically induced, or precisely edited, alongside conventional genetic selection, using tools such as epigenome wide association studies and epigenetic quantitative trait locus mapping to identify useful epialleles before deciding whether to

fix them permanently through targeted editing (Chen et al., 2025). Nanoparticle delivered CRISPR epigenome editing fits naturally into this pipeline as the tool that converts a promising natural epiallele, once identified, into something that can be installed intentionally and at scale.

VII. CHALLENGES AND KNOWLEDGE GAPS

A fair review has to be honest about how much is still unresolved. Heritability is the biggest open question. Somatic priming effects can fade once the stress is removed, and even genuinely transgenerational epigenetic marks are not always stable across many generations, since plant cells have active demethylation and chromatin resetting pathways that can erase an edit over time unless it is reinforced. Off target epigenetic drift is a second concern, and the comparative profiling work on dCas9 methylation editors makes clear that more potent multiplexed effectors tend to bring more unintended methylation changes elsewhere in the genome, a trade off that has not been fully solved.

Delivery efficiency is the third major gap, and it is specific to moving from model species to real crops. Most of the strongest carbon nanotube delivery results come from Arabidopsis, tobacco, and a handful of leafy or young tissue systems, and reaching germline or meristem tissue reliably, which matters if the goal is heritable transmission rather than just a transient effect in the treated plant, remains much less well demonstrated. Cargo size is a related practical constraint, since the more powerful multiplexed epigenome editors, CRISPRoff for example, run large enough to exceed the packaging capacity of some delivery vehicles, which pushes designers back toward smaller, single effector constructs that may be less potent.

Finally, there is a genuine evidence gap in the convergence itself. As noted in Section 5, no single published study surveyed for this review has yet demonstrated the complete pipeline, nanoparticle delivery of a CRISPR epigenome editor producing a validated, heritable, field relevant stress tolerance trait in a major crop. Everything proposed in Section 5 is a reasoned extrapolation from adjacent, well supported work, not a reported result, and any reader building on this review should treat it accordingly.

VIII. REGULATORY AND BIOSAFETY CONSIDERATIONS

Regulatory treatment of this technology is still unsettled in most jurisdictions, and it depends heavily on two technical details: whether any foreign DNA integrates into the genome, and whether the final product carries a permanent change to the DNA sequence or only a reversible epigenetic mark. Transgene free nanoparticle delivery, where the cargo is degraded after use and no foreign sequence remains, is generally expected to face a lighter regulatory path than classical transgenic approaches, similar to the treatment already extended to some DNA free CRISPR edited crops in certain countries. Epigenetic edits complicate this picture further, since they change gene expression without changing the DNA sequence at all, and regulatory frameworks built around the

presence or absence of novel DNA sequence do not map cleanly onto a technology that leaves the sequence untouched.

There are also biosafety questions specific to nanomaterials themselves, including the environmental fate of nanoparticles applied at agricultural scale, potential toxicity to non-target organisms, and the practicalities of large-scale, cost-effective nanoparticle synthesis for field level deployment rather than laboratory scale leaf infiltration. These are engineering and toxicology questions as much as they are plant biology questions, and they will need dedicated environmental risk assessment before any nanoparticle delivered epigenome editing product could reach commercial agriculture.

IX. FUTURE DIRECTIONS

A few concrete research directions stand out. Building smaller, single domain epigenome editors specifically optimised for nanoparticle packaging would help close the cargo size gap described above. Systematic testing of germline and meristem targeted delivery, rather than leaf infiltration alone, is needed if heritable transmission is the actual goal rather than a one generation effect. Longer term field trials tracking epigenetic mark stability across multiple generations under real stress conditions, rather than single controlled greenhouse exposures, would give a much more honest picture of durability. Finally, closer collaboration between the epigenetics, CRISPR tool development, and nanomaterials communities, who currently publish largely in separate journals and rarely cite each other's most recent work, would likely accelerate exactly the kind of integrated pipeline this review has sketched out.

X. LIMITATIONS OF THIS REVIEW

Two limitations are worth stating plainly. First, this review leans on English language, primarily open access literature retrieved through standard academic search, and it is possible that relevant work in regional agricultural journals or in preprint form was missed. Second, and more importantly, the central synthesis in Section 5 is a conceptual integration built from three separate, independently well supported literatures rather than a summary of directly reported convergence experiments, since very few such experiments currently exist in print. Readers should treat Section 5 as a research proposal grounded in existing evidence, not as a report of demonstrated results, and should verify the current state of the field before citing it as established fact, since this is a fast-moving area and new integrated studies may appear soon after this review is written.

XI. CONCLUSION

Epigenetic stress memory, CRISPR based epigenome editing, and nanoparticle mediated delivery are each, on their own, well established and rapidly advancing areas of plant science. Bringing them together offers a genuinely plausible route to climate resilient crops that could be developed

faster than conventional breeding allows and with a lighter regulatory footprint than classical transgenics, because the approach can avoid both permanent DNA sequence change and foreign DNA integration. The pieces needed to build this pipeline already exist in the literature. What remains is the harder, more patient work of connecting them end to end, proving that the resulting stress memory is heritable and stable, and testing all of this under real field conditions rather than controlled laboratory ones. That is the work this field now needs to take on.

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Determination of Water Quality Index and Suitability of Groundwater at Dudhwada Village at Padra Industrial Area, Vadodara, Gujarat

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***Abstract*—The approach of the study is to calculate the water quality index of the peri-urban area in seasonal basis of Vadodara district to ensure the utilization of groundwater for domestic, agricultural, and industrial purposes. The focus of study the deal with environmental parameters of groundwater at this area. We are various approach to assess the water quality of groundwater and its suitability based on the results obtained. In this study, various parameters were assessed for evaluating the groundwater quality include Colour, pH, Total Alkalinity (as CaCO3), Ammonical Nitrogen, Electrical Conductivity, Chloride, Fluoride, Turbidity, Total Dissolved Solids, Nitrate, Sulphate, Calcium, Sodium, Potassium, Magnesium, Total Hardness, Nickle (as Ni), Copper (as Cu), Lead (as Pb), Total Arsenic (as As), Total Chromium (as Cr6+), Cadmium, Selenium, Mercury (as Hg), and Cobalt.**

***Index Terms*—Water Quality Index, seasonal variance, Aquifers, Peri-urban, groundwater**

I. INTRODUCTION

Water is a useful resource for every living creature on Earth. Water is the most distinctive feature and a necessity for everyone. Water is required for every activity, from drinking to agriculture and industrialization. In India, groundwater is the single largest source of drinking water and is withdrawn from various sources like wells, tube wells, hand pumps, and submersible pumps. This is easily reachable and accessible, and is considered less polluted as compared to surface water like ponds, rivers, lake, canals, and other manmade reservoir, however, cleaning groundwater is more difficult compared to surface water once contaminated as required a lot of resources and expenses. Water demand is increasing day by day due to urbanization, infrastructure development, industrialization, population growth, and agricultural activity, which

directly impacts the exploitation of groundwater. Disposal of untreated sewage in the soak pit in the urban area directly impacts the groundwater, and small-scale industries are releasing the untreated effluent on bare land, which is later mixed with rainwater and recharges the groundwater. Based on various studies, heavy metals are carcinogenic as they create various health-related issues in persons once injected through water or the food chain, and long-term exposure causes issues related to the kidney, liver, nervous system, and cancer. In the past, researchers have verified the use of groundwater quality for the detection WQI, which provides the overall pollution level of groundwater aquifers.

II. MATERIAL AND METHOD

During the study, Dudhawada villages were selected for seasonal variation. The current study aims to evaluate groundwater samples from the selected area and verify the WQI. Padra, Karkhadi, and Jambusar are the oldest GIDCs in the Vadodara region. Various industries are situated in the nearby Dudhawada village, including chemicals, pharmaceuticals, agrochemicals, and pigments. Groundwater used by villagers for agriculture activity is having red color and pageant smell, along with various significant issues. The water used by the public in the study region for different purposes is polluted, and the public is experiencing severe health issues. As a result, this study aims to provide an overview of actual groundwater quality. Measurements of quantitative parameters in groundwater serve as a milestone to address basic environmental problems based on the IS standard/ WHO. Various researchers' assessments of groundwater quality in peri-urban areas revealed that very little work has been done on pollution indices, so this study aims to evaluate the groundwater quality at the sampling area using HPI.

Groundwater quality has been determined by collecting 48 samples in the Peri-urban area of the Vadodara region, for example, from April 2024 to March 2026; however, changes are shown for seasonal basis only. Samples were collected in 1.0-liter clean sample bottles, with proper details like name, location, date, and other necessary information, and analysis was performed at an NABL-approved laboratory according to APHA 23rd Edition

III. LITERATURE REVIEW

Many scholar has worked on these topics as Farzana et al. (2025) looked into the quality of groundwater in Ishwardi Upazila, a peri-urban area in Bangladesh, where there wasn't much previous data on drinking water safety. They gathered 35 samples from deep tube wells and tested for things like pH, EC, TDS, and various metals. Using atomic absorption spectroscopy, they found that levels of bicarbonate, iron, and manganese often went beyond the safe limits set by Bangladesh, Ravi Kant Dubey et.al, Ground Water Quality and Water Quality Index of Dwarka District of the National Capital of India. Sridhar et al. (2025) assessed the seasonal distribution, ecological hazards, and human health implications of uranium and associated heavy metals in groundwater throughout Krishnagiri district, Tamil Nadu, India. The research gathered 42 groundwater samples during the 2024 monsoon and 2025 post-monsoon periods, analyzing

physicochemical parameters and elements including uranium, barium, beryllium, bismuth, cesium, copper, gallium, manganese, and strontium by ICP-OES methodology, Singh et al. (2024) assessed groundwater quality in the Bathinda area of Punjab, India, where extensive exploitation of groundwater has occurred due to intensive agricultural activities in the semi-arid region. The research evaluated the appropriateness of groundwater for potable use using the Drinking Water Quality Index and investigated non-carcinogenic health concerns linked to fluoride and nitrate exposure in adults and children by oral intake and cutaneous absorption, Kaur et al. (2023) analyzed groundwater quality and the pathways of nitrate and fluoride enrichment across various basins in Punjab, India, utilizing 323 groundwater samples. The research employed hydro-geochemical modeling, graphical representations, multivariate statistics, an entropy-based water quality index, and Monte Carlo simulation to evaluate groundwater quality and associated health hazards

IV. METHODOLOGY

One of the simplest methods to evaluate the water quality condition is by using the water quality index. This procedure provides meaningful summaries of water quality data that are meaningful for both technical and non-technical individuals and organization interest in water quality results. The Water Quality Index is one of the easiest and most effective methods to communicate information on groundwater quality to the concerned citizens and policymakers. It thus becomes an important parameter for the assessment of groundwater quality. The groundwater quality index is the simplest number that expresses the overall quality of water of a certain location based on various water quality parameters. The water quality index was calculated using the weighted arithmetic index used by Sanjib Das et. al. (2014)

Arithmetic Procedure: Computation of the Water Quality Index is mainly done in five steps;

1- Each of the parameters is assigned a weightage factor (wi) according to its relative importance in the overall quality of water for drinking purposes. The minimum weight of 1 has been assigned to the parameter acidity as it plays an insignificant role in the water quality assessment. Other parameters were assigned a weightage factor between 1 and 5 depending on their importance.

2- In the second step, relative weight (Wi) is computed from the following equation;

$$Wi = \frac{wi}{\sum_{ni=1} Wi}$$

N= no of Parameter

3- In the third step, a quality rating scale (qi) for each parameter is assigned by dividing its concentration in each sample (Ci) by its respective standard (Si) according to the guideline laid down in the BIS, and the resultant is multiplied by 100.

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$$qi = \frac{Ci}{Si} \times 100$$

4- In this step, Sub index (SI) of each parameter is calculated by the following equation;

$$SI = Wi \times qi$$

5- Finally, the water quality index (WQI) is calculated by adding all the sub-indices of all parameters at a location,

$$WQI = \sum SI$$

Table 1 Water Quality Index (WQI) and Status of Groundwater Quality (Chatterjee and Raziuddin 2002)

Table 1: Drinking water standard Water Quality Standard values and relatives' weight of parameter.

Sr. No	Parameters	Standard (Si)	wi	Wi
1	Color	5	3	0.0222
2	pH@25C	6.5	4	0.0296
3	Total Alkalinity (as $CaCO_3$)	200	3	0.0222
4	Ammonical Nitrogen	0.5	4	0.0296
5	Electrical Conductivity	800	2	0.0148
6	Chloride	250	5	0.0370
7	Fluoride	1	5	0.0370
8	Turbidity	1	1	0.0074
9	Total Dissolved Solids	500	5	0.0370
10	Nitrate	45	5	0.0370
11	Sulphate	200	4	0.0296
12	Calcium	75	2	0.0148
13	Sodium	20	2	0.0148
14	Potassium	12	2	0.0148
15	Magnessium	30	2	0.0148
16	Total Hardness	200	2	0.0148
17	Nickle (as Ni)	0.02	4	0.0296
18	Copper (as Cu)	0.05	4	0.0296
19	Lead (as Pb)	0.01	4	0.0296
20	Total Arsenic (as As)	0.01	5	0.0370
21	Chromium (as Cr6+)	0.05	4	0.0296
22	Cadmium	0.003	4	0.0296
23	Selenium	0.01	4	0.0296
24	Mercury (as Hg)	0.001	4	0.0296
25	Cobalt	0.05	5	0.0370

V- RESULTS AND DISCUSSION

A total of 48 Samples collected between April 2024 to march 2026 from two locations of Dudhawada village, Vadodara district and later analyzed in an NABL-approved laboratory for their physicochemical parameters including Colour, pH, Total Alkalinity (as CaCO3), Ammonical Nitrogen, Electrical Conductivity, Chloride, Fluoride, Turbidity, Total Dissolved Solids, Nitrate, Sulphate, Calcium, Sodium, Potassium, Magnesium, Total Hardness, Nickle (as Ni), Copper (as Cu), Lead (as Pb), Total Arsenic (as As), Total Chromium (as Cr6+), Cadmium, Selenium, Mercury (as Hg), and Cobalt. Based on the calculation method of the WQI, groundwater sample were failed and need treatment for using any kind of application.

Table 2: Seasonal variation of the physicochemical parameters of the water body

Sr. No	Parameters	Summer Season (May' 2025)	Rainy Season (August' 26)	Winter Season (October' 26)
1	Color	4434.00	3278.00	4231.00
2	pH@25C	6.73	6.98	6.70
3	Total Alkalinity (as $CaCO_3$)	255.73	215.23	265.67
4	Ammonical Nitrogen	8.02	9.24	8.25
5	Electrical Conductivity	8543.23	7897.34	8609.28
6	Chloride	2897.67	2897.23	2886.78
7	Fluoride	0.00	0.00	0.00
8	Turbidity	54.27	51.45	56.78
9	Total Dissolved Solids	4048.49	3978.28	4232.45
10	Nitrate	0.00	0.00	0.00
11	Sulphate	582.96	531.23	576.89
12	Calcium	244.76	216.56	245.49
13	Sodium	497.45	523.43	496.67
14	Potassium	53.89	54.78	54.56
15	Magnessium	621.77	627.38	618.78
16	Total Hardness	3186.78	3276.34	3278.00
17	Nickle (as Ni)	0.03	0.03	0.00
18	Copper (as Cu)	0.63	0.53	0.59
19	Lead (as Pb)	0.01	0.01	0.00
20	Total Arsenic (as As)	0.17	0.16	0.00
21	Chromium (as Cr6+)	0.01	0.02	0.15
22	Cadmium	0.00	0.00	0.00
23	Selenium	0.00	0.00	0.05
24	Mercury (as Hg)	0.00	0.00	0.00
25	Cobalt	0.00	0.00	0.05

Table 3: Calculation of Water Quality Index in Summer Season

Parameter	Standard (Si)	Dudhwada Result (ci)	wi	Wi	qi=ci/Si*100	SI=Wi* qi
Color	5	4434.00	3	0.0222	88680.000	1970.667
pH@25C	6.5	6.73	4	0.0296	103.538	3.068
Total Alkalinity (as $CaCO_3$)	200	255.73	3	0.0222	127.865	2.841
Ammonical Nitrogen	0.5	8.02	4	0.0296	1604.000	47.526
Electrical Conductivity	800	8543.23	2	0.0148	1067.904	15.821
Chloride	250	2897.67	5	0.0370	1159.068	42.928
Fluoride	1	0.00	5	0.0370	0.000	0.000
Turbidity	1	54.27	1	0.0074	5427.000	40.200
Total Dissolved Solids	500	4048.49	5	0.0370	809.698	29.989
Nitrate	45	0.00	5	0.0370	0.000	0.000
Sulphate	200	582.96	4	0.0296	291.480	8.636
Calcium	75	244.76	2	0.0148	326.347	4.835
Sodium	20	497.45	2	0.0148	2487.250	36.848
Potassium	12	53.89	2	0.0148	449.083	6.653
Magnessium	30	621.77	2	0.0148	2072.567	30.705
Total Hardness	200	3186.78	2	0.0148	1593.390	23.606
Nickle (as Ni)	0.02	0.03	4	0.0296	164.000	4.859
Copper (as Cu)	0.05	0.63	4	0.0296	1260.000	37.333
Lead (as Pb)	0.01	0.01	4	0.0296	124.000	3.674
Total Arsenic (as As)	0.01	0.17	5	0.0370	1690.000	62.593
Chromium (as Cr6+)	0.05	0.01	4	0.0296	25.600	0.759
Cadmium	0.003	0.00	4	0.0296	0.000	0.000
Selenium	0.01	0.00	4	0.0296	0.000	0.000
Mercury (as Hg)	0.001	0.00	4	0.0296	0.000	0.000
Cobalt	0.05	0.00	5	0.0370	0.000	0.000
Water Quality Index of Summer Season:						2373.541

Table 4: Calculation of Water Quality Index in Rainy Season

Parameter	Standard (Si)	Dudhwada Result (ci)	wi	Wi	qi=ci/Si*100	SI=Wi* qi
Color	5	3278.00	3	0.0222	65560.000	1456.889
pH@25C	6.5	6.98	4	0.0296	107.385	3.182
Total Alkalinity (as $CaCO_3$)	200	215.23	3	0.0222	107.615	2.391

Ammonical Nitrogen	0.5	9.24	4	0.0296	1848.000	54.756
Electrical Conductivity	800	7897.34	2	0.0148	987.168	14.625
Chloride	250	2897.23	5	0.0370	1158.892	42.922
Fluoride	1	0.00	5	0.0370	0.000	0.000
Turbidity	1	51.45	1	0.0074	5145.000	38.111
Total Dissolved Solids	500	3978.28	5	0.0370	795.656	29.469
Nitrate	45	0.00	5	0.0370	0.000	0.000
Sulphate	200	531.23	4	0.0296	265.615	7.870
Calcium	75	216.56	2	0.0148	288.747	4.278
Sodium	20	523.43	2	0.0148	2617.150	38.773
Potassium	12	54.78	2	0.0148	456.500	6.763
Magnessium	30	627.38	2	0.0148	2091.267	30.982
Total Hardness	200	3276.34	2	0.0148	1638.170	24.269
Nickle (as Ni)	0.02	0.03	4	0.0296	156.000	4.622
Copper (as Cu)	0.05	0.53	4	0.0296	1064.000	31.526
Lead (as Pb)	0.01	0.01	4	0.0296	122.000	3.615
Total Arsenic (as As)	0.01	0.16	5	0.0370	1580.000	58.519
Chromium (as Cr6+)	0.05	0.02	4	0.0296	33.400	0.990
Cadmium	0.003	0.00	4	0.0296	0.000	0.000
Selenium	0.01	0.00	4	0.0296	0.000	0.000
Mercury (as Hg)	0.001	0.00	4	0.0296	0.000	0.000
Cobalt	0.05	0.00	5	0.0370	0.000	0.000
Water Quality Index of Rainy Season:						1854.550

Table 5: Calculation of Water Quality Index in Winter Season

Parameter	Standard (Si)	Dudhwada Result (ci)	wi	Wi	qi=ci/Si*100	SI=Wi* qi
Color	5	4231.00	3	0.0222	84620.000	1880.444
pH@25C	6.5	6.70	4	0.0296	103.077	3.054
Total Alkalinity (as $CaCO_3$)	200	265.67	3	0.0222	132.835	2.952
Ammonical Nitrogen	0.5	8.25	4	0.0296	1650.000	48.889
Electrical Conductivity	800	8609.28	2	0.0148	1076.160	15.943
Chloride	250	2886.78	5	0.0370	1154.712	42.767
Fluoride	1	0.00	5	0.0370	0.000	0.000
Turbidity	1	56.78	1	0.0074	5678.000	42.059

Total Dissolved Solids	500	4232.45	5	0.0370	846.490	31.351
Nitrate	45	0.00	5	0.0370	0.000	0.000
Sulphate	200	576.89	4	0.0296	288.445	8.547
Calcium	75	245.49	2	0.0148	327.320	4.849
Sodium	20	496.67	2	0.0148	2483.350	36.790
Potassium	12	54.56	2	0.0148	454.667	6.736
Magnessium	30	618.78	2	0.0148	2062.600	30.557
Total Hardness	200	3278.00	2	0.0148	1639.000	24.281
Nickle (as Ni)	0.02	0.00	4	0.0296	0.000	0.000
Copper (as Cu)	0.05	0.59	4	0.0296	1186.000	35.141
Lead (as Pb)	0.01	0.00	4	0.0296	0.000	0.000
Total Arsenic (as As)	0.01	0.00	5	0.0370	0.000	0.000
Chromium (as Cr6+)	0.05	0.15	4	0.0296	290.000	8.593
Cadmium	0.003	0.00	4	0.0296	0.000	0.000
Selenium	0.01	0.05	4	0.0296	456.000	13.511
Mercury (as Hg)	0.001	0.00	4	0.0296	0.000	0.000
Cobalt	0.05	0.05	5	0.0370	95.200	3.526
Water Quality Index of Winter Season:						2239.991

VI. CONCLUSION

Water Quality Index		Outcome of Sample
Excellent (0–25):	Highest quality, suitable for all drinking purposes.	0
Good (26–50):	Slight pollution, acceptable for drinking and domestic use.	0
Poor (51–75):	Moderately polluted, requires treatment before consumption.	0
Very Poor (76–100):	Heavily polluted, not recommended for human consumption.	0
Unsuitable (>100:	Excessively polluted, hazardous, and unsuitable for drinking	3

The analysis result indicates that the quality of Dudhawada villages is highly polluted and requires strict regulatory action to prevent further pollution. Almost every parameters are above the prescribed limit by the WQI as BIS, As the rapid growth of industrialization in said region

required proper treatment of effluent at industry side and further secondary treatment by Government common effluent treatment plant for further treatment before release to deep sea.

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Current and Future Trends in Technology Integration by College Faculty

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***Abstract*—The teaching profession, a noble profession, has evolved with changing times to reflect societal shifts and technological breakthroughs. From the traditional classroom which involved usage of blackboard, chalk and textbooks, where teaching was done using the "chalk and talk" method, to the emergence of smart classrooms and blended learning, each job component of a college teacher, including teaching, evaluation, research, learning and development and administrative duties have undergone tremendous change. The purpose of this paper is to study the current and future trends of ICT and AI-based technology usage in higher education, in context of each job role of a college faculty.**

Technology has widespread usage in teaching and learning and has brought about a paradigm shift in teaching practices. The advent of Artificial Intelligence (AI) technology has been rapid and is fast evolving. Technology tools have completely changed the ways in which lectures are delivered. With the availability of vast e-resources, learning is now easier. Tools such as ChatGPT and Gemini have made research work quicker. Usage of AI-driven technology is becoming widespread very rapidly, bringing with it a new set of opportunities and challenges.

***Index Terms*—Technology, Artificial Intelligence (AI), Teacher, Higher Education, Job components**

I. INTRODUCTION

In modern times, technology has pervaded all aspects of life. From the days of chalk and blackboard, the process of teaching and learning has kept on evolving with changing technology. The introduction of AI has brought about far-reaching changes in every aspect of teaching profession. Each component of a teacher's job can now be carried out by integrating technology, making learning interactive and informative.

1.1. The emergence of technology in education

Information and Communication Technology (ICT) is referred to as the diverse range of technological tools and resources used for information generation, dissemination, administration and communication. ICT consists of hardware, software and network infrastructure.

ICT tools have revolutionized the landscape of higher education, offering university faculty a dynamic range of resources to enhance teaching, research, and administration. The integration of ICT tools into academia facilitates innovative pedagogical approaches, enabling instructors to create more interactive and engaging learning environments. From smart classrooms which include digital whiteboards, projectors, power point presentations, USB, cables and laptops to Enterprise Resource Planning (ERP) software, which is used to track student attendance and performance and Blended Learning, which is a hybrid method of learning combining face-to-face and online mode, thereby providing flexibility of study time and location, these technologies empower educators to tailor their teaching methods, reach a broader audience, and manage their academic responsibilities more efficiently. Additionally, ICT plays a crucial role in fostering research and learning by providing access to webinars, online Faculty Development Programmes (FDPs), vast digital libraries, plagiarism check, grammar check and paraphrasing tools. As universities continue to evolve in a digital age, the adept use of ICT tools by faculty is essential for improving educational outcomes of students and for their own professional development in a technology-driven world.

II. OBJECTIVES

The paper aims, through a literature survey,
To study how each component of a college teacher's job has been integrated with technology.
To enumerate the current and futuristic technology tools that can be used for each component of a faculty.
To examine the benefits and challenges of technology usage by faculty.

III. METHODOLOGY

This is a conceptual paper and the data for the same is collected through secondary sources. For the purpose of Literature Review, Google Scholar was searched to collect journal articles using keywords such as "ICT in Education", "Challenges of technology usage" etc.
Data was also collected from other sources such as thesis and websites for the purpose of enumerating the various job roles of a faculty and the tools used to help perform them.

IV. REVIEW OF LITERATURE

a) Zafar, T. (2019). [1] examines role, challenges and impact of ICT on students, teachers and end-users. The study finds a positive impact of ICT usage on students' collective capabilities and skills.

b) Ratheeswari, K. (2018). [2] calls for a well-designed teacher training programme so that ICT tools can be effectively used for teaching.

c) Rani, M, et. al. (2023). [3] Through a survey of 60 teachers, the paper underlines a need for teacher training in using ICT tools.

d) Singh, V, Dubey, A, & Sonkar, C (2022). [4] Through a literature analysis, the study examined the changes introduced in education system such as blended learning, evaluative learning, learning through blogging etc.

e) Janaki, P. (2019). [5] Finds a positive influence on quality of education through ICT. Using a sample size of 17 teachers and 40 students, the paper recommends that ICT can be effective only when teachers are digitally literate and trained to use ICT.

f) Pandey, A. & Kamlesh S.R. (2023). [6] The paper provides an overview of various ICT tools used in education field and studies advantages and disadvantages of these tools and also examines the role of policy and infrastructure in effective integration of ICT in education.

g) Saha, T. (2023). [7] The paper discusses the role of ICT in education and the issues and challenges in the process. Suggests financial and technical support, policy formulation and teacher's training.

h) Jo Shan Fu (2013). [8] This review paper studies merits of integrating ICT in schools, barriers and challenges in implementation, teacher's attitudes, perception and confidence in using ICT.

i) Sharma, A. (2021). [9] Finds that school teachers use ICT in lesson planning, lesson delivery and assessments. The paper also highlights Government efforts to integrate ICT into the education system.

j) Singh, J., & Kumari, M (2022). [10] Studies the role of ICT in Indian education from 35 universities. Finds that teachers prefer using ICT tools in classrooms. Students also reported a positive impact of ICT.

k) Kumar, K. (2023). [11] Notes the increasing use and impact of ICT in the higher education system. Discusses the role played by in continuing education during the pandemic. The paper also calls for increased involvement of teachers in using ICT.

l) Ghavifekr, S., et. al. (2016). [12] In a study of 100 secondary school teachers in Meleka state Malaysia, found that challenges faced included problems with network connection, lack of training and lack of competency in using ICT.

m) Jena, R. K. (2015). [13] examined the stress levels among academicians resulting from use of ICT tools, by studying technostress among 216 academicians randomly selected from different

colleges across India. Observed that increased technostress reduces satisfaction, commitment and performance.

n) Scherer, R., Siddiq, F., & Teo, T. (2015). [14] The study conducted among 1653 Norwegian teachers, finds a positive correlation between self-efficacy and ICT tools but a negative relation to age.

o) Olulube, P. (2006). [15] Studied the impact, uses and challenges of integrating ICT in teachers' education program in Nigeria and showed dissatisfaction among the 180 respondents studied, with the pace of ICT integration.

p) Chigona, A., Chigona, W., & Davids, Z. (2014). [16] Investigates factors that motivate teachers to use ICTs in schools in disadvantaged areas of South Africa. Finds that satisfaction derived from using ICT, individual expectations and a sense of achievement experienced while using technology are some factors that motivate use of ICT tools.

q) Oye, N. D., Iahad, N. A., & Rabin, Z. A. (2011). [17] Using the TAM & UTAUT models, studied teachers' behavioural intention on acceptance and use of technology among 100 respondents from a University in Nigeria. Finds that performance expectancy is the most influential factor for use of ICT by the respondents. The study recommends mandatory training for teachers to use ICT.

r) Mikre, F. (2011). [18] The paper analyses the benefits and limitations of ICT in education. The paper studies the challenges and impact of ICT usage in the Ethiopian context. Concludes that despite the limitations, use of ICT improves the quality of education programmes and is useful to enhance student engagement and has a positive impact on student performance and achievement.

s) Lomos, C., Luyten, J. W., & Tieck, S. (2023). [19] Luxembourg has one the highest availability of technology related resources of teaching and learning, but a relatively lower use of technology in classrooms. Using a data of 420 teachers in Luxembourg, the study finds internal barriers such as skills, attitude and knowledge are responsible for low use. The study also finds personal characteristics of teachers such as vision, beliefs and perception of utility of ICT are predictors of ICT usage.

t) Fitria, T. N. (2021). [20] The paper discusses the various uses of AI in education, and notes that use of AI in routine tasks such as grading, recoding student attendance, generating admin reports, will be made easier. This will enable teachers to better perform their job duties. The paper notes that while AI is a powerful tool, it cannot replace teachers.

u) Crompton, H., & Burke, D. (2023). [21] This systematic review examines the use of AI in higher education from 2016 to 2022. Around 138 articles were studied. The purpose of using AI was identified as assessment/evaluation and managing student learning.

V. FINDINGS, RESULT AND DISCUSSIO

Table 1: Job Components of a college faculty and scope for technology usage

Job Component of a college faculty	ICT Tools used		Current and future trends of AI-driven technology
Classroom teaching		Hardware Tools	
• Creation of lesson plan • Preparation of PPT/Slides • Delivering Lectures • Preparation and sharing of Study Material • Field Trips	• Smart Classroom • Blended Learning • YouTube • MS office (PowerPoint, word) • Websites & Search engine (eg. Google) • Google Classroom • Videoconferencing Platforms (Zoom, Google meet etc.) • Learning Management System (LMS)	• Projector • Wi-Fi • Laptop • USB • Smart Board • Cable	• AI-driven Presentation tools (eg. Canva/ Prezi) • Virtual field trips using Virtual reality (VR) • Curriculum design using Machine Learning (ML) and Generative AI. • Augmented Reality (AR) • Gamification
Administrative duties		Hardware Tools	
• Attendance • Internal marks • Student committee work • Class teacher duties • Mentoring students • Administrative Positions (eg. Dean) • Parent-teacher communication • Staff meetings	• Enterprise Resource Planning (ERP) • E-mail	• WIFI • Laptop	• AI-based attendance system through facial recognition. • Support through automated administrative tasks (helps to reduce teacher workload)
Evaluation		Hardware Tools	
• Question Paper setting • Valuation or	• Online Quiz (Internal Assessment through ERP or Google Forms)	• Computer lab • Internet	• Plagiarism check software (eg. Turnitin)

grading • Internal Assessment • Invigilation • Preparing exercises/activities.	• MS Office (Word, Excel)	connection (LAN)	• AI-based proctored examination • Grading tools (eg. Gradescope) • Assessments through generative AI [22] & Natural language processing (NLP) powered tools • Auto descriptive answer Evaluation [23].
Research		Hardware Tools	
• Publications • Conference Presentations • Funded Projects • Guiding students for projects/ Ph.D.	• Article Databases/Search engine (Google Scholar/CrossRef/Research Gate etc.) • Reference Management Software (eg. Mendeley, Zotero etc.) • Repository (Shodhganga/INFLIBNET) • Statistical Analysis Software (eg. SPSS, R etc.)	• Laptop • Wi-Fi	• AI Chatbots (eg. ChatGPT) • Paraphrasing Tool (eg. Quillbot) • Grammar Check software (eg. Grammarly) • Plagiarism check software (eg. Turnitin)
Learning and Professional Development		Hardware Tools	
• Updating knowledge	• Digital Library (Databases, e-books, e-journals, repositories) • MOOCs (eg. Coursera, SWAYAM, Udemy, LinkedIn Learning etc.) • E-learning (Online FDPs, Webinars)	• Wi-Fi • Laptop • Library with desktop and internet connection	• AI generated personalized course recommendations (eg. Coursera) [24] Customized learning modules

5.1. Current and Future trends of Artificial Intelligence (AI) and other technology in Education

AI is revolutionizing teaching in higher education by streamlining tasks and enhancing pedagogical methods. Currently, AI is being used by faculty members to automate grading, manage

administrative duties, enable faster research work and provide analytics on student performance to tailor instruction. Tools like virtual teaching assistants and AI-driven content creation platforms help educators focus on core teaching activities. AI tools are assisting faculty members with creating educational content, such as lesson plans, presentations, and interactive modules. Virtual Reality (VR) technologies, powered by AI, can create immersive and engaging learning experiences, through virtual field trips.

In the future, AI is expected to enable more dynamic and personalized learning environments, support faculty in research by analyzing large datasets, and foster collaboration through intelligent virtual platforms. AI can automate tasks like grading and providing feedback, freeing up teachers' time for more focused interactions with students. AI can help to analyse student performance data, providing immediate feedback and insights to students, their parents and teachers. AI will also likely revolutionize invigilation through AI-based proctored examinations, leading to more efficient and effective online assessments, thereby reducing the need for physical invigilation.

Additionally, AI will play a key role in professional development by offering customized learning modules based on individual teaching styles and needs.

Some types and uses of this AI technology is described in detail below:

a) AI Chatbots

An AI chatbot is a computer program that uses artificial intelligence to simulate conversations with human users, often used in higher education to automate tasks, provide instant support, and offer personalized learning experiences.

ChatGPT is one the most popular AI-powered chatbots used in education. Teachers can use ChatGPT to generate answers to open-ended questions [25], thereby helping them to prepare instruction material for their classes. It also makes tasks such as writing research papers quicker and easier.

b) Paraphrasing Tools

A paraphrasing tool is software that rewrites or rephrases text while preserving the original meaning, offering alternative phrasing for words, phrases, sentences, or even paragraphs. In higher education, teachers can use these tools for research, to improve writing, understand complex texts, and avoid plagiarism.

c) AI-driven presentation tools

An AI-driven presentation tool uses artificial intelligence to assist in creating, designing, and delivering presentations, offering features like content generation, layout suggestions, and multimedia integration. It helps teachers make more visually appealing presentation slides, thereby acting as a valuable tool in making classroom teaching more interesting.

d) Virtual Reality (VR)

VR uses technology to simulate environments and objects, making users feel like they are present in that virtual world. VR creates immersive, interactive, 3D simulated environments, and college

teachers can use it to enhance learning by offering hands-on simulations, virtual field trips, thereby providing students access to otherwise inaccessible experiences.

e) Grammar Check Software

AI based Grammar check software analyses text for errors in grammar, spelling, punctuation, and style, and college teachers can use it to save time on grading, provide students with feedback on their assignments, and also helps faculty in research writing.

f) Plagiarism check software

Plagiarism check software, like Turnitin, helps higher education teachers identify instances of plagiarism by comparing student work against a vast database of published materials and the internet, generating similarity reports to highlight potential issues. It can be used to evaluate student papers, assignments and projects.

Newer AI-driven plagiarism detection tools help to check for AI-generated texts and helps in controlling use of AI assistance [26].

g) Grading tools

AI-based grading tools use artificial intelligence to automate and streamline the grading process in higher education, offering teachers time-saving solutions and providing students with faster feedback. These tools analyse student work, provide feedback, and can even assist with creating assessments. AI algorithms can automatically grade multiple-choice questions, fill-in-the-blank questions, and even some short-answer questions, saving teachers significant time. Some tools allow teachers to input rubrics, and the AI can then grade based on those criteria, ensuring consistency and fairness.

5.2. Constraints or Challenges of Technology usage in Education

A few challenges posed by technology integration in education include

- Digital divide in terms of access to internet and other IT infrastructure as well as access to digital libraries between institutions in rural and urban areas or between elite and non-elite educational institutions or between those who know to use and do not know.
- Drop in thinking skills or creativity due to rise in AI Chatbots
- Rise in plagiarism caused by use of paraphrasing tools.
- Stress of adapting to changing technology i.e., technostress.
- Data privacy concerns.
- Cost of access and maintenance.
- Lack of awareness about technology tools/ Lack of training
- Addiction to devices or gadgets.
- Need for continuous learning to use emerging technology tools.
- Tiredness/health problems caused by use of devices.
- Overload of information.

VI. SCOPE FOR FURTHER RESEARCH

There is need for a primary data-based study to analyse the extent of technology usage and further detailing what factors facilitate early adoption and optimum utilization of these technologies by higher education teachers.

VII. CONCLUSION

Integration of technology into teaching and learning has revolutionized the education system. Furthermore, technology is rapidly evolving and newer AI tools are set to bring about more rapid changes. The use of technology has the power to make teaching and learning a more fulfilling experience. However, technology poses certain challenges like information overload, use of technology by students for leisure activities and lack of creativity. It is essential that only the positive aspects of technology have to be used.

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