Digital farming and smart agriculture: Data driven decisions for sustainable agriculture

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Abstract-Digital farming is transforming agriculture by addressing rising food demand, climate challenges, resource scarcity, and environmental degradation. By integrating technologies such as IoT, UAVs, AI, robotics, and data-driven decision-support systems, it enhances precision in resource use, boosts crop and livestock productivity, and minimizes environmental impacts. IoT-based sensors, automated irrigation, and smart gateways enable real-time monitoring and optimized water and nutrient management, while UAVs facilitate precision spraying, field mapping, and cost-effective input application. AI-driven analytics strengthen yield prediction, disease detection, and overall decision-making. Key applications include precision crop monitoring, variable-rate technologies, predictive modelling, climate-smart advisories, and digital supply chain platforms. However, adoption faces challenges such as high initial costs, limited rural infrastructure, low digital literacy, data privacy concerns, and socio-cultural resistance. Addressing these barriers through government support, affordable solutions, improved connectivity, and farmer training can accelerate progress. Overall, digital farming offers a pathway to climate-smart, economically viable, and resilient agriculture, contributing significantly to sustainable development and global food security.

Index Terms - UAVs, Artificial Intelligence, Precision Agriculture IoT, Variable Rate Technology and Decision Support Systems

I. INTRODUCTION

Global agriculture is confronting a complex set of challenges. Rapid population growth, changing dietary patterns, and rising demand for food put pressure on agricultural systems worldwide. Also, climate change, land degradation, water scarcity, and environmental concerns demand that food production becomes more resource-efficient and ecologically sustainable. Traditional farming practices often based on uniform application of water, nutrients, and agrochemicals are increasingly inadequate to meet these twin demands of productivity and sustainability. Many nations like India still employ the old manner of farming; farmers are unwilling to use sophisticated technology when farming due to either a lack of expertise, high costs, or because they are uninformed of the advantages of these technologies [1].

Fig: 1 A conceptual view of different aspect in digital and smart agriculture

Smart farming represents the next leap in agricultural evolution, integrating Information and Communication Technology (ICT) into farming practices. Defined as the application of IoT, AI, robotics, and digital technologies in agriculture, smart farming aims to enhance productivity, sustainability, and profitability [2]. IoT devices, such as sensors and drones, collect data on soil moisture, crop health, and environmental conditions. AI and machine learning algorithms analyse this data to inform decisions on planting, watering, and harvesting. Robotics automates labour-intensive tasks, reducing the need for human labour and increasing precision in activities such as planting, weeding and harvesting. The significance of smart farming extends beyond mere technological advancement; it addresses pressing global challenges. With the world population projected to reach 9.7 billion by 2050, food production must increase significantly to meet demand [3]. Smart farming offers a pathway to increase food production while minimizing environmental impacts. By optimizing resource use and reducing waste, smart farming practices contribute to sustainability and climate change mitigation efforts. Additionally, smart farming technologies can enhance food security by increasing crop yields and reducing losses due to pests, diseases, and environmental factors. In livestock farming, AI and machine learning are being leveraged for computer vision-based body weight estimation, early detection of health issues in dairy cows, and UAV-enabled pasture monitoring (Fig. 1). Collectively, these innovations aim to enhance efficiency, sustainability, and automation across diverse agricultural domains [4].

II. TECHNOLOGIES USED IN DIGITAL FARMING

Internet of things:

The Internet of Things (IoT) is essential for modernizing various sectors, particularly agriculture. A study in Saudi Arabia indicated that when farmers are aware of IoT technologies, they are more likely to perceive their benefits and be willing to adopt them for tasks like crop monitoring. For small and medium-sized businesses (SMEs), implementing IoT means an incremental business model change that unfolds through inception, experimentation, and replication [5,6]. However, family-managed firms tend to be risk-averse and focused on family goals, leading them to prefer exploitative IoT innovations (improving existing practices) over exploratory ones (new, untested ones), a preference intensified by technological diversification [7].

Sensors are the driving force behind this agricultural shift, enabling data-driven, efficient, and sustainable farming. Experts believe the future of agricultural sensor applications is bright, promising to redefine global food production[8]. Specifically, automated, sensor-based irrigation systems can significantly optimize water use, cut costs, and boost productivity [9]. The IoT gateway is crucial for these systems, acting as a communication hub between sensors (measuring temperature, humidity, soil moisture, and light) and cloud platforms. These smart irrigation systems are vital for addressing water scarcity and can potentially increase crop yields by 25% while allowing for remote management [10,11].

III. UNMANNED AERIAL VEHICLES (UAVS) IN AGRICULTURE

UAVs (Drones) represent a significant upgrade over conventional farming methods, offering a more efficient and cost-effective way to spread seeds and fertilizers. A major advantage is that they do not damage crops during flight or compact the soil, ensuring fertilizer is evenly distributed[12]. Drones can rapidly treat large areas (e.g., 1.5 hectares in 10 minutes), substantially cutting labour costs and enabling rapid, automated spreading. They also allow farmers to sow seeds efficiently in hard-to-reach areas like wetlands [13].

Drones are primarily used in farming for tasks like monitoring crops, applying chemicals with high precision, taking aerial photos, mapping fields, and spreading fertilizer [14]. Some reports show overall cultivation costs drop by 30% [15]. Labour costs also fall, particularly compared to manual work (one study showed a 17.57% labour cost reduction). Farmers see yield increases up to 6.89% and profit gains between 14% and 26% [16].One five-year study on wheat suggests the potential for 40% less fertilizer use, which also increases income as yields rise. Overall, adopting precision agriculture with drones lowers costs per acre and dramatically increases net profits (one example showed total expenses dropping from 27,723.20 to 22,857.50).One study recorded an astounding 92% to 96% reduction in water use. Herbicide use was lowered by 36% to 38%. Farmers saw 5% to 40% less fertilizer use, resulting in corresponding decreases in the use of pest [17].

IV. EFFECTS OF AI-DRIVEN INTERVENTIONS

Artificial intelligence (AI) is proving to be much better than old-fashioned farming methods, leading to measurable improvements in how efficiently farms use resources and manage crops[18]. AI technology significantly conserves vital inputs: it cuts water use by 55%, reduces energy consumption by 51%, and lowers fertilizer use by 20% compared to traditional practices. In terms of crop health and output, using AI systems instead of manual methods boosts overall crop yield by 20% and makes predicting the final harvest 0.40% more accurate [19]. Furthermore, specialized AI applications are incredibly precise, hitting 98.4% accuracy when forecasting exactly how much water crops need and achieving up to 90% accuracy in diagnosing plant diseases [20].

V. APPLICATION

1.Precision Crop Monitoring:

Digital farming facilitates continuous, high-resolution observation of crop growth through satellite imaging, UAV-based remote sensing, and machine learning algorithms. These technologies enable early detection of biotic and abiotic stresses, allowing for timely interventions and improved crop management strategies[31].

2.Variable Rate Input Application (VRT):

VRT technologies adjust the application rate of seeds, fertilizers, and pesticides according to spatial variability within fields. By utilizing prescription maps generated from soil analyses, yield data, and geospatial models, VRT supports site-specific input management and minimizes resource wastage [32].

3.Soil and Environmental Sensing Systems:

Networks of soil sensors, loT devices, and environmental monitoring platforms provide real-time measurements of soil moisture, nutrient status, temperature, and microclimate conditions. These datasets support more precise irrigation scheduling, nutrient management, and risk assessment [33].

4.Smart Irrigation and Water-Use Optimization:

Automated irrigation systems integrate field sensors, remote weather data, and evapotranspiration (ET) models to regulate water application with high accuracy. AI-driven controllers adjust irrigation schedules dynamically, promoting water conservation and reducing energy consumption [34].

5.Decision Support Systems (DSS) and Predictive Modelling:

Digital DSS platforms combine field data, weather forecasts, crop models, and machine learning techniques to guide management decisions. These systems assist in forecasting yield, predicting pest and disease outbreaks, and optimizing planting or harvesting schedules [35].

6.Robotics and Automated Farm Machinery:

The adoption of autonomous tractors, robotic weeders, drone sprayers, and automated planters reduces labour requirements and enhances operational precision. Robotics contributes to sustainable intensification by improving resource-use efficiency and reducing chemical overuse [36].

7.Digital Market Platforms and Supply Chain Traceability:

Digital agriculture strengthens market linkages through e-commerce platforms, digital payment systems, and blockchain-based traceability. These tools improve transparency, support quality assurance, and enhance farmers' access to competitive markets [37].

8.Climate-Smart Digital Tools:

ICT-enabled weather advisories, climate-risk models, and early-warning systems help farmers respond more effectively to climatic uncertainties. Digital tools support climate-smart agriculture by improving adaptation planning and reducing vulnerability to extreme conditions [38].

9.Precision Livestock Management:

Digital livestock systems incorporate biosensors, automated feeding equipment, RFID identification, and behaviour monitoring tools. These technologies enable early disease detection, optimize feed use, and improve overall animal welfare [39].

VI. ADVANTAGES

Digital farming enhances sustainability by improving resource efficiency, profitability, and quality of life in agriculture.

- Environmentally, tools like sensors, drones, and GPS systems reduce water use, chemical use, and carbon emissions while enabling early pest and disease detection.
- Economically, precision techniques boost yields, lower input costs, improve supply chain transparency, and help farmers manage climate risks.
- Socially, automation reduces labour demands, supports better decision-making, and makes farming more appealing to younger generations.

VII. DIGITAL FARMING FACES SEVERAL LIMITATIONS THAT SLOW ITS ADOPTION

- High initial costs for equipment like sensors, drones, and software make it unaffordable for many farmers, especially smallholders.
- Weak rural infrastructure—such as poor internet connectivity, unreliable electricity, and complex technologies—creates operational challenges.
- Data-related issues also play a major role: inaccurate data can lead to wrong decisions, and farmers often worry about data privacy, ownership, and misuse.
- Social and cultural barriers exist, including resistance to new technologies among traditional farmers and concerns that automation may reduce employment opportunities in rural communities.

VIII. CONCLUSION

Digital farming represents a transformative pathway toward achieving sustainable, productive, and resilient agriculture by integrating advanced technologies such as IoT, UAVs, AI, robotics, and data-driven decision-support systems to overcome many limitations of traditional farming practices. These innovations enable precise resource management, enhance crop and livestock productivity, reduce environmental impacts, and open new economic opportunities for farmers. However, despite these promising benefits, widespread adoption remains hindered by high initial costs, limited rural infrastructure, low digital literacy, data privacy concerns, and cultural resistance among traditional farming communities. Addressing these challenges will require coordinated efforts from governments, technology developers, and educational institutions to ensure equitable access, affordability, and farmer-friendly solutions. Overall, digital farming offers a powerful means to meet rising global food demands while promoting environmental stewardship and economic well-being, and with the right support systems, capacity building, and inclusive innovation, it can play a central role in shaping a sustainable and food-secure future for generations to come.

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