Development and Characterization of IR-Reflective HDPE Composite Film for Thermal Regulation in Agrotextile Applications

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Abstract- This research is based on the development and evaluation of high-density polyethylene (HDPE) film reinforced with titanium dioxide (TiO_2), having the potential to reflect near-infrared (NIR) radiation. for its use in agrotextile shade-nets developments. The aim is to reduce the temperature inside the agrotextile shade net by reducing heat buildup without compromising visible light transmission. Twin-screw extrusion process was used for the development of HDPE composite film by incorporating different concentrations of TiO_2 (0.1–0.7 wt%) pigment. The developed film was characterized to assess TiO_2 particle dispersion, IR reflectance, and light diffusion properties. The results showed that HDPE film containing 0.5 wt% TiO_2 particles had an IR reflectance of 20.87% and 84% visible light transmission. These results indicate the potential of TiO_2-infusion in HDPE polymer matrix as a practical and energy-efficient solution for thermal control in Agrotextile shade-net applications.

Index-Terms: Crop improvement, Photosynthesis, Shade net, Titanium dioxide, UV resistance

I. INTRODUCTION

In recent years, shade-net structures have gained considerable popularity in tropical and subtropical regions as a practical and affordable option for protected cultivation. Farmers, especially small and marginal growers, prefer shade nets because they offer a cost-effective solution to manage the microclimate for optimal plant growth by moderating sunlight intensity. These agrotextiles help reduce heat stress on plants and often contribute to improved crop quality and higher yields.

Despite these advantages, a major technical challenge under shade-net cultivation remains maintaining favourable air temperature and relative humidity levels for optimal plant growth, as Shade-net house structures have lower ventilation rates than open fields. Due to a low ventilation rate, the shade net structure is inefficient in removing excess heat. While natural ventilation can work under moderate climatic conditions, its effectiveness depends heavily on the temperature gradient between the inside and outside air (buoyancy effect) and wind speed (wind effect). In hot and dry climates, where ambient temperatures frequently reach 42–45°C and relative humidity is below 15%, these passive systems become ineffective. In such a scenario, warm internal air is replaced with hot external air, resulting in no significant cooling benefit.

Supportive cooling solutions, such as fans, coolers, or air conditioners, are routinely used in polyhouse structures; however, they are energy-intensive and economically unviable for small or marginal farmers. High-end technologies, such as evaporative cooling systems, liquid radiation filters (LRFs), and thermal control films, have shown positive results in polyhouse cultivation. However, most of these techniques are impractical for use in shade-net houses due to their high costs.

Due to these limitations, there is a need for a passive and cost-effective thermal regulation method suitable for shade-net applications. The focus of this research work is to address that gap by developing an infrared (IR)-interactive polymeric material, particularly high-density polyethylene (HDPE) films incorporated with titanium dioxide (TiO_2). The research is based on understanding the characteristics of incoming solar radiation and identifying the wavelengths that contribute to a rise in temperature without having any benefits to plants with respect to photosynthesis.

Sunlight that reaches the Earth is composed of three major components: ultraviolet (UV) light, visible light, also known as photosynthetically active radiation (PAR), and infrared (IR) light. UV forms only about 5%, PAR makes up around 45%, and the remaining 50% is IR radiation.

Within the IR region, the wavelength band from 700 to 1100 nm, known as near-infrared (NIR) radiation, is primarily responsible for heat buildup. While PAR is essential for plant growth and photosynthesis, NIR does not benefit plants in any way; its only effect is to increase the temperature inside protected structures, which is undesirable.

Using materials that reflect near-infrared (NIR) light while maintaining visible light transmission can effectively reduce internal temperatures in protected structures, such as shade-net houses. Recent work has shown that using IR-reflective films in naturally ventilated polyhouse structures significantly reduces the head load inside the structures and supports optimal crop growth conditions [1]. Another study showed that metal oxide-incorporated plastic films also reduced the temperature in the greenhouse, which helps save energy [2]. These materials can hence minimize heat accumulation while still supporting plant photosynthesis. Recent work also demonstrated that TiO_2-incorporated polyethylene films achieve high near-infrared reflectance up to 54% which effectively reduces an average 6.7 °C temperature in greenhouse structures [3].

In addition, reflective and diffusive polyethylene films have been reported to improve greenhouse microclimate and crop yield under arid conditions [4].

This study proposes the development of an IR-reflective composite film by incorporating TiO_2 particles into HDPE polymer matrix followed by the conversion of the developed HDPE composite into a tape yarn suitable for agrotextile shade-net development. Titanium dioxide is selected due to its high refractive index, strong IR scattering properties, and excellent UV durability. The work involves a multi-stage material development process including film extrusion, tape yarn production, and shade-net development with the aim of producing a smart, IR-interactive material that passively reduces heat load and enhances light quality without affecting its mechanical properties and is also suitable for agrotextile product development.

II MATERIALS AND METHODS

The materials used in the development of the IR-reflective HDPE composite films are as follows:

- High-Density Polyethylene (HDPE): HDPE is a Molecule of polyethylene having a long chain of carbon atoms with two hydrogen atoms attached to each carbon atom. This linear polymer is used as the base matrix. It has a high strength-to-density ratio but requires stabilization for UV resistance properties. HDPE is also widely used in commercially available agrotextile shade nets.
- UV Stabilizer: Shade-nets are used in outdoor applications; hence they should withstand outdoor environmental conditions. UV is one of the most important environmental factors affecting the life of the HDPE as the polymer is very sensitive to UV degradation. UV light promotes the degradation of HDPE polymer through free radical reactions. Hence, if HDPE is used in its neat form, it will not survive the weather conditions. So, modification of the HDPE polymer is essential for its usage in Shade-net. UV-absorbing materials have been incorporated into the HDPE matrix used to provide sufficient UV protection. 2 wt% UV-absorbing additives were added to increase UV resistance and reduce UV-induced degradation of the polymer.
- Green Colour Masterbatch: Incorporated during film extrusion to achieve the characteristic shade-net colour and to improve light diffusion.
- Infrared (IR) Reflective Pigment: The Infrared Radiation is responsible for the heat built up, which is also desired, but nowadays it goes beyond the acceptable limit, and most of the time reaches an extreme level during the summers. In this work, IR-responsive pigments are incorporated into the HDPE matrix to develop an IR reflective HDPE film.

2.1 Composite Preparation via Melt Compounding

The incorporation of UV stabilizers and IR-reflective pigments into the HDPE matrix was achieved using a melt compounding technique on a twin-screw compounder, a process ideal for uniform additive dispersion in polymers.

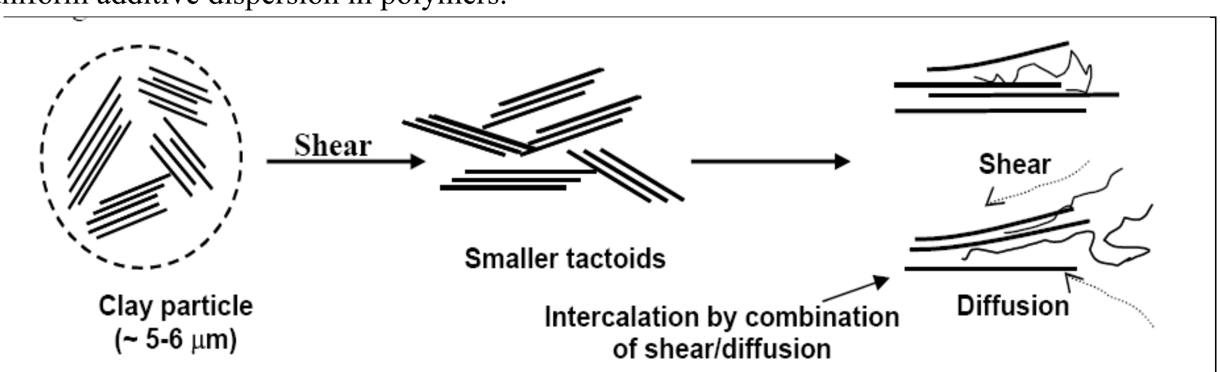

Figure 1: Melt Compounding

Table 1: Machine Specification

Parameter	Specification
Manufacturer	Boolani Engineering Pvt. Ltd.
Max. Screw Speed	1200 rpm
L/D Ratio	40
Motor Power	5 kW
Pelletization Method	Strand cutting
Vacuum Capability	380 mmHg

Seven composite variants (C1 to C7) were formulated by varying the IR pigment content from 0.1% to 0.7% by weight. Extruder screw speeds and barrel temperature profiles were optimized to ensure effective pigment dispersion while avoiding polymer degradation. The resulting composites were collected.

2.2 Development of HDPE composite Film using Blown Film Extrusion

The compounded HDPE composite was processed using the Blown Film Extrusion method, which produces biaxially oriented films with uniform mechanical properties. Using the technique, the compounded polymer was converted into films.

The molten polymer is extruded through a circular die, inflated into a bubble using controlled air pressure, cooled with an air ring, and flattened via nip rollers. Parameters such as blow-up ratio, drawdown rate, and cooling profile were adjusted for each formulation. Final films were labelled F1 to F5 and served as the basis for all subsequent characterizations.

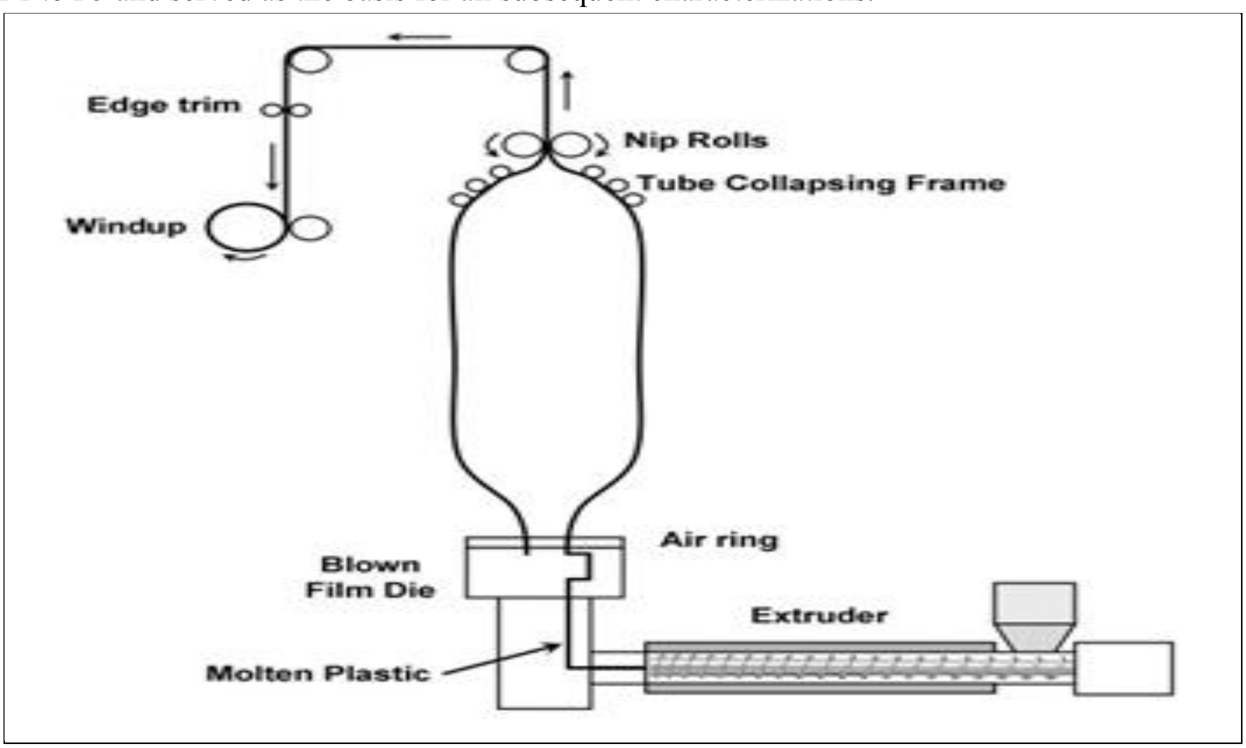

Figure 2: Film Blowing Process

2.3 Characterization of HDPE Composite Film

To understand the performance of the developed IR-reflective HDPE films, various analytical tests were conducted.:

- Melting Point Analysis - Melting point is a key thermal parameter that defines processing and end-use temperature limits of polymers. The neat HDPE polymer and developed HDPE composite films were tested for Melting point using:
    - Instrument: Simultaneous Thermal Analyzer
    - Make: Perkin Elmer, USA
    - Model: STA 6000
    - Heating Rate: 20 °C/min

  Similar analysis was carried out for thermal characterization of TiO_2–HDPE nanocomposites using DSC analysis [5], confirming that Tio_2 loading significantly influences crystallization behaviour and heat of fusion.
- Optical Transmission (400–700 nm) - Visible light transmission is a key factor for photosynthesis, and agrotextile materials must allow maximum transmission of sunlight in the PAR range. Hence, the developed HDPE composite Film light transparency was measured using:
    - Equipment: UV-Vis Spectrophotometer
    - Make: Shimadzu, Japan
    - Model: UV-2600
    - Wavelength Range: 400–700 nm
- IR Reflectance (700–2500 nm) - To test the composite film's ability to reflect NIR reflectance was measured using the UV-Vis spectrophotometer in the IR spectrum. Both virgin HDPE and composite films were tested for comparison.
    - Equipment: UV-Vis Spectrophotometer
    - Make: Shimadzu, Japan
    - Model: UV-2600
- IR Efficiency - IR efficiency refers to the percentage of incoming IR radiation (700–2500 nm) that is blocked or reflected by the film. It indicates a holistic measure of the material's ability to mitigate heat load. Hence, the developed samples were also assessed for their IR efficiency.

III. RESULTS AND DISCUSSION

This study focuses on developing an IR-reflective HDPE composite film designed to reduce heat buildup in agrotextile shade nets. Titanium dioxide (TiO_2), known for its ability to reflect near-infrared (NIR) radiation, was incorporated into the HDPE matrix to develop films that can reduce thermal load. The films were produced through optimized melt-compounding and extrusion processes. Various properties, including thermal behaviour, IR reflectance and efficiency, light transmission, and diffusion, were studied. The results showed how Variation of TiO_2

concentrations influences film performance and also help understand the mechanism for the development of effective, heat-reducing materials for agricultural applications.

3.1 Optimisation of Compounding Conditions

HDPE-based composites (C1–C7) were developed with increasing concentrations of IR reflective pigment (0.1–0.7 wt%). The melt compounding process was optimized for each formulation. As additive loading increased, both the barrel temperature and dwell time also increased, indicating the need for higher energy input to ensure homogeneous mixing at higher viscosities (Table 2 and 3).

Table 2: Temperature profile of twin screw compounder

Composite	Temperature (^{0}C) profile of the twin screw compounder									
	B1	B2	B3	B4	B5	B6	B7	B8	DA	DH
C1	140	142	145	147	150	153	158	160	162	165
C2	141	144	145	148	150	154	156	160	161	166
C3	142	144	146	149	151	155	156	161	165	166
C4	143	145	147	150	152	154	153	158	162	166
C5	144	145	148	151	152	153	154	158	160	167
C6	147	148	149	154	156	158	159	161	165	169
C7	152	155	157	158	162	165	167	168	171	173

While formulations up to 0.5 wt% (C5) maintained stable thermal processing windows and good dispersion, further increases (C6, C7) required significantly higher shear and dwell time, potentially leading to polymer degradation.

Table 3: Dwell time for composite development

Material	Dwell Time (sec)
C1	120
C2	120
C3	160
C4	165
C5	175
C6	225
C7	260

3.2 Development of IR-Responsive Films

Using the optimized composites, seven blown films (F1–F7) were fabricated. Increasing pigment content required higher extrusion temperatures and adjustments to the blow/expansion ratios (Tables 4 and 5). While F1–F5 maintained good drawability, F6 and F7 exhibited reduced expansion ratios, likely due to compromised melt strength resulting from matrix degradation, consistent with later mechanical and thermal performance trends.

Table 4 - Developed composite film

Composite Film	Loading Level % (w/w)
F1	0.10
F2	0.20
F3	0.30
F4	0.40
F5	0.50
F6	0.60
F7	0.70

Table 5: Temperature profile of film blowing process

Material	Temperature (^{0}C) profile of the extruder		
	Zone 1	Zone 2	Cross Head
F1	171	175	180
F2	171	176	182
F3	172	177	183
F4	173	178	184
F5	174	178	185
F6	175	179	186
F7	176	179	186

3.3 Thermal Behaviour – Melting Point Analysis

The melting points of virgin HDPE and all developed composite films were assessed (Table 6, Fig. 3). Up to a 0.5 wt% pigment loading, only marginal decreases in melting point (~0.6–1.1°C) were observed, indicating good thermal stability. However, C6 and C7 showed a significant drop to (132.12 °C and 130.20 °C), suggesting that high-temperature exposure during compounding induced polymer chain degradation.

Table 6: Melting point values of HDPE and composites

Material	M.P. (^{0}C)
Unprocessed HDPE	135.50
Processed HDPE	135.45
C1	134.82
C2	134.71
C3	134.52

C4	134.45
C5	134.40
C6	132.12
C7	130.20

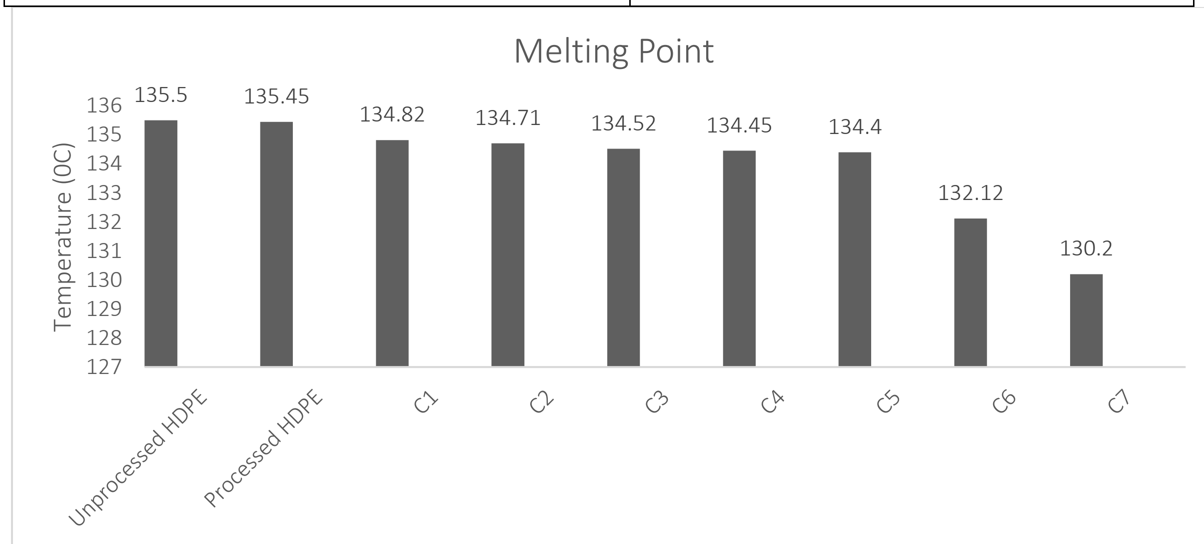

Figure 3: Melting Point of the HDPE composite

3.4 Optical Properties – Light Transmission and Diffusion

Light transmission in the photosynthetically active radiation (PAR) range (400–700 nm) decreases with increasing pigment loading (Table 7, Figure 4). Virgin HDPE showed 89% transmission, whereas F5 (0.5 wt%) retained 84.2%, reduction. Beyond this level (F6, F7), light transmission dropped significantly (<80%), which could hinder photosynthetic efficiency in actual crop cultivation.

Table 7- Light transmission

Sample	Total Light (%)
Virgin HDPE Film	89.0
F1	87.9
F2	87.1
F3	86.2
F4	85.5
F5	84.2
F6	79.3
F7	74.4

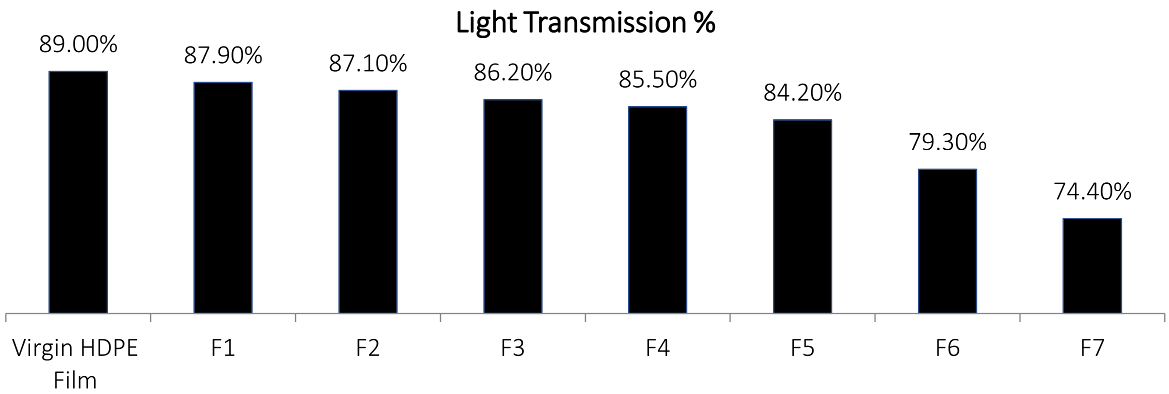

Figure 4: Light Transmission

In contrast, diffused light improved with higher pigment content (Table 8, Figure 5), rising from 8.1% in virgin HDPE to 43.6% in F7. Increased light diffusion can be beneficial for uniform canopy lighting and reduced leaf scorch, indicating a trade-off between total transmission and light quality.

Table 8 - Diffused light

Sample	Diffused Light (%)
Virgin HDPE Film	8.1
F1	19.5
F2	25.6
F3	29.5
F4	32.6
F5	38.2
F6	41.2
F7	43.6

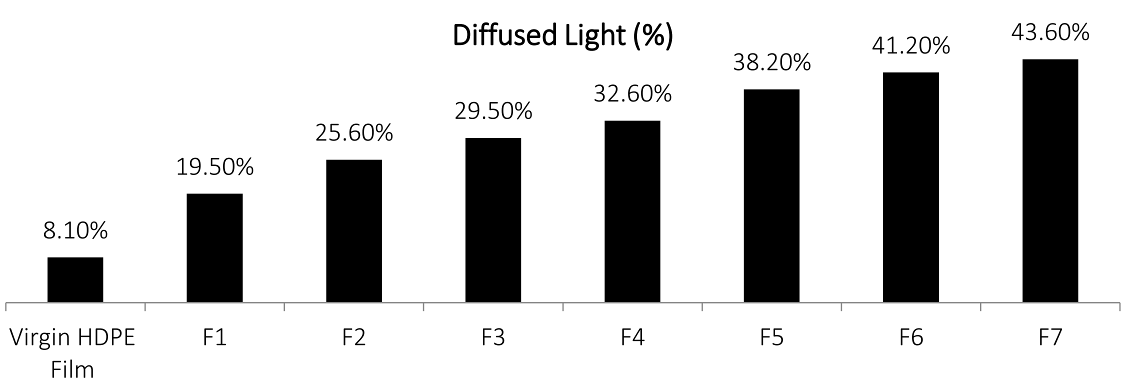

Figure 5: Diffusion of Light

3.5 Near-Infrared Reflectance

The developed composite film's ability to reflect NIR radiation was significantly enhanced by the integration of an IR reflective pigment. While virgin HDPE showed <1%, the IR reflectance in the 800–1120 nm range, which further improved steadily across samples F1to F7, reaching the highest 20.87 % reflectance in F7 (Table 9). This trend confirms the pigment's effectiveness and its proper dispersion within the matrix, particularly optimum in C5–C7 samples.

Table 9 - Infrared Reflectance

Wavelength (nm)	Virgin HDPE Film (%)	F1 (%)	F2 (%)	F3 (%)	F4 (5)	F5 (%)	F6 (%)	F7 (%)
800	0.09	5.35	5.66	5.87	6.14	7.01	7.01	7.01
820	0.10	7.51	8.59	9.87	11.10	15.12	15.12	15.12
840	0.12	7.87	9.89	11.57	13.31	18.35	18.35	18.35
860	0.14	9.75	12.47	13.53	16.35	17.46	17.98	18.46
880	0.18	12.34	15.68	14.31	15.74	16.13	17.53	18.13
900	0.19	15.65	16.11	18.63	19.15	19.22	19.45	19.62
920	0.20	16.21	16.85	17.47	17.82	18.11	18.71	19.34
940	0.23	16.30	17.26	18.11	18.65	19.12	19.62	19.90
960	0.24	16.85	17.56	17.95	18.13	18.64	18.94	19.34
980	0.26	17.03	17.65	17.91	18.12	18.74	18.94	19.44
1000	0.33	17.25	18.43	18.91	19.45	20.21	20.33	20.52
1020	0.35	17.36	17.89	18.71	19.34	20.19	20.39	20.65
1040	0.37	17.85	17.58	18.95	19.56	20.31	20.45	20.67
1060	0.39	18.01	17.91	18.99	19.81	20.21	20.31	20.43
1080	0.41	18.21	17.93	19.35	19.92	20.15	20.45	20.61
1100	0.45	18.33	18.13	19.51	20.14	20.26	20.41	20.54
1120	0.47	18.54	18.63	19.74	20.16	20.67	20.77	20.87

IV. CONCLUSION

This study developed IR-reflective high-density polyethylene (HDPE) composite films for agrotextile applications with the aim of developing shade nets capable of reducing temperature when used in protected cultivation systems. Titanium dioxide (TiO_2)-based IR-responsive pigments were incorporated into the HDPE polymer matrix through melt compounding, and films were extruded using the Film Blowing Process with different Titanium dioxide (TiO_2) pigment concentrations and developed films were characterized for their performance.

The results indicate that integration of TiO_2 to the HDPE polymer matrix enhances the film's ability to reflect near-infrared (NIR) radiation, which is largely responsible for heat buildup inside shade-net structures. At the same time, the composite films maintained high visible light transmission and desired light-diffusion properties, which are essential for photosynthesis. However, TiO_2 integration into HDPE matrix above 0.5 wt% negatively affects the material properties by lowering the melting point and also reduces the expansion ratio during film formation which ultimately leads to polymer degradation.

Among all the developed variants, the film containing 0.5 wt% TiO_2 (F5) demonstrated the best overall performance, recording an optimum IR reflectance of 19.22% at 900 nm while maintaining the desired optical and thermal behaviour. Based on the findings from this work, TiO_2-modified HDPE composite films show strong potential as a scalable, energy-efficient material for the development of agro shade nets, which can reduce heat load in shade-net structures, especially during the summer season.

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