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**Synergistic Effect of CNT–TiC Photothermal Coating and Internal Radiation Reflector
on the Thermal Performance of a Hemispherical Solar Greenhouse**

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Synergistic Effect of CNT–TiC Photothermal Coating and Internal Radiation Reflector on the Thermal Performance of a Hemispherical Solar Greenhouse

Abstract

The development of durable photothermal coatings is an effective approach for improving the thermal performance of solar energy systems. In this study, a carbon nanotube–titanium carbide (CNT–TiC) nanocomposite coated heat transfer medium integrated with an internal radiation reflector was developed for a hemispherical solar greenhouse. The coating was characterized using X-ray diffraction, scanning electron microscopy, and ultraviolet–visible spectroscopy. Thermal performance was evaluated under stagnation, natural convection, and operating conditions with and without the internal radiation reflector. A Photothermal Temperature Contribution (PTTC) index was introduced to quantify the coating contribution under identical solar exposure. The integrated system attained a maximum temperature of 78.4 °C, a PTTC value of 89.7%, and a thermal efficiency of 82.1%. The combined effect of the CNT–TiC coated heat transfer medium and internal radiation reflector enhanced useful heat gain and reduced thermal losses, demonstrating an effective passive strategy for improving hemispherical solar greenhouse performance.

Keywords: Carbon nanotube–titanium carbide; Nanocomposite coating; Photothermal absorber; Solar greenhouse; Thermal efficiency

1. Introduction

Solar thermal technologies have attracted considerable attention as sustainable alternatives for meeting the growing demand for low-temperature thermal energy in agricultural, industrial, and domestic applications [1]. Among these technologies, solar greenhouses are widely employed because they provide a controlled thermal environment using renewable solar energy [2]. Their performance, however, is strongly influenced by the ability of the absorber surface to capture solar radiation and retain the generated heat within the enclosure. A significant fraction of the incident solar energy is often lost through reflection and re-radiation, which limits the overall thermal efficiency of conventional greenhouse systems [2,3].

Several approaches have been reported to improve the thermal performance of solar greenhouses, including selective absorber coatings, nanomaterial-based photothermal surfaces, phase change materials, thermal energy storage systems, and reflective components [4-6]. Carbon-based nanomaterials have received particular attention because of their excellent

optical absorption, high thermal conductivity, and chemical stability. Carbon nanotubes (CNTs) exhibit broadband solar absorption and rapid photothermal conversion, making them attractive candidates for solar absorber coatings [7,8]. Titanium carbide (TiC), on the other hand, possesses high thermal stability, mechanical durability, and efficient heat transfer characteristics [9,10]. These properties suggest that combining CNT and TiC may produce a robust photothermal coating capable of improving solar heat absorption under outdoor operating conditions.

Passive radiation management has also emerged as an effective method for improving solar thermal systems without increasing energy consumption. Internal reflectors can redirect transmitted solar radiation towards the absorber surface, increasing the interaction between the incoming radiation and the photothermal material [11,12]. Although photothermal coatings and passive reflector systems have individually demonstrated promising performance, their combined influence on the thermal behaviour of hemispherical solar greenhouses has received limited attention. Furthermore, most previous studies have focused on greenhouse performance alone, with limited effort devoted to quantifying the independent contribution of the photothermal coating before system integration.

In the present study, a CNT–TiC nanocomposite photothermal coating was developed and integrated with an internal radiation reflector to improve the thermal performance of a hemispherical solar greenhouse. The developed coating was characterized using X-ray diffraction, scanning electron microscopy, and ultraviolet–visible spectroscopy to evaluate its structural, morphological, and optical properties. The thermal response of the coated heat transfer medium was first investigated under outdoor atmospheric conditions and subsequently evaluated after integration into the greenhouse. In addition, a Photothermal Temperature Contribution (PTTC) index is introduced to quantify the standalone contribution of the developed coating under identical solar exposure. The combined material–system approach presented in this work provides an effective strategy for improving solar energy utilization through enhanced photothermal conversion and passive radiation recovery, with potential applications in solar greenhouses and other low-temperature solar thermal systems.

2. Materials and Methods

2.1. Preparation of CNT–TiC nanocomposite photothermal coating

Multi-walled carbon nanotubes (CNTs) and nanosized titanium carbide (TiC) were used as the photothermal constituents for developing the nanocomposite coating. The coating composition was prepared by mixing CNTs and TiC in a weight ratio of 70:30. The prepared nanomaterials were dispersed in a commercially available solar-grade black coating emulsion and mixed using a mechanical stirrer until a homogeneous suspension was obtained [13].

The heat transfer medium was thoroughly cleaned with acetone and distilled water to remove dust, grease, and surface contaminants before coating. The prepared nanocomposite suspension was deposited on the cleaned surface using a spray coating technique. During coating, the spray rate was maintained at 10 mL min^{-1} , compressed air was used as the carrier gas, and the distance between the spray nozzle and substrate was maintained at 15 cm to obtain a uniform coating [13,14]. The coated samples were cured in a hot air oven at 120°C for 1 h to improve coating adhesion and stability. The average coating thickness was maintained at $18 \pm 2 \text{ }\mu\text{m}$.

The prepared CNT–TiC coated heat transfer medium was visually examined before characterization and thermal evaluation. The deposited coating exhibited good surface uniformity without visible peeling, cracking, or discontinuities after curing. The developed coating was subsequently subjected to structural, morphological, optical, and outdoor thermal investigations.

2.2. Characterization of the developed coating

The structural characteristics of the developed CNT–TiC nanocomposite coating were examined using X-ray diffraction (XRD) analysis with Cu-K α radiation ($\lambda = 1.5406 \text{ }\text{\AA}$). The diffraction patterns were recorded over an appropriate scanning range to identify the crystalline phases present in the coating. The crystallite size of the deposited nanocomposite was estimated using the Debye–Scherrer equation: $D = k \lambda / (\beta \cos \theta)$, where where D is the crystallite size (nm), K is the shape factor, λ is the wavelength of the X-ray source, β is the full width at half maximum of the diffraction peak, and θ is the Bragg diffraction angle. The surface morphology of the developed coating was examined using a ZEISS EVO-18 scanning electron microscope (SEM). The SEM micrographs were used to evaluate the surface uniformity, particle distribution, and microstructural features of the deposited CNT–TiC coating. The optical characteristics of the nanocomposite coating were analysed using ultraviolet–visible (UV–Vis)

spectroscopy over the selected wavelength range. The recorded absorption spectrum was used to assess the light absorption behaviour of the CNT–TiC coating within the solar spectral region and to examine its suitability as a photothermal absorber.

2.3. Outdoor thermal evaluation of the coated heat transfer medium

The thermal behaviour of the developed CNT–TiC coated heat transfer medium was evaluated under outdoor atmospheric conditions and compared with that of a non-coated heat transfer medium of identical dimensions. Both specimens were exposed simultaneously to natural solar radiation under identical environmental conditions to ensure a direct comparison. During experimentation, the samples were positioned to avoid shadowing and external disturbances throughout the test period [15].

The surface temperature of the coated and non-coated heat transfer media was recorded at regular time intervals during sunshine hours. Simultaneously, the incident solar radiation, ambient temperature, and wind speed were monitored using calibrated instruments. The recorded data were used to evaluate the influence of the CNT–TiC coating on solar heat absorption under natural outdoor conditions.

To quantify the thermal contribution of the developed photothermal coating, a Photothermal Temperature Contribution (PTTC) index was introduced. The PTTC index represents the percentage increase in the temperature of the coated heat transfer medium relative to the non-coated reference under identical solar exposure and is expressed as:

$$\text{PTTC (\%)} = \frac{T_c - T_{nc}}{T_{nc}} \times 100 \quad (2)$$

where T_c is the temperature of the CNT–TiC coated heat transfer medium (°C) and T_{nc} is the temperature of the non-coated heat transfer medium (°C). A higher PTTC value indicates a greater contribution of the photothermal coating towards solar-to-thermal energy conversion. The recorded temperature profiles and PTTC values were subsequently used to assess the standalone performance of the developed coating before its integration into the hemispherical solar greenhouse.

2.4. Experimental investigation of the hemispherical solar greenhouse

The thermal performance of the hemispherical solar greenhouse integrated with the CNT–TiC coated heat transfer medium was evaluated under outdoor environmental conditions. The

hemispherical greenhouse used in the present investigation was fabricated according to the design specifications reported in the authors' earlier work, while the current study introduces an internal radiation reflector to improve the utilization of transmitted solar radiation within the enclosure [16]. The experimental hemispherical solar greenhouse, its schematic representation, and the internal radiation reflector used in the present study are shown in figures 1–3, respectively.



Figure 1. Experimental hemispherical solar greenhouse used for outdoor thermal performance evaluation under natural solar radiation

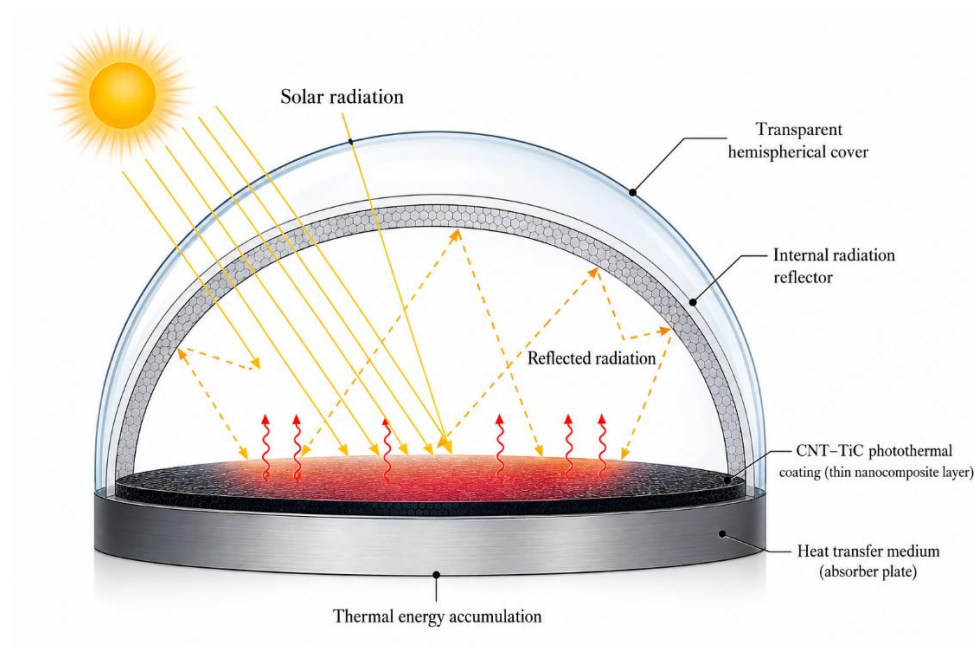


Figure 2. Schematic illustration of the experimental hemispherical solar greenhouse integrated with the internal radiation reflector

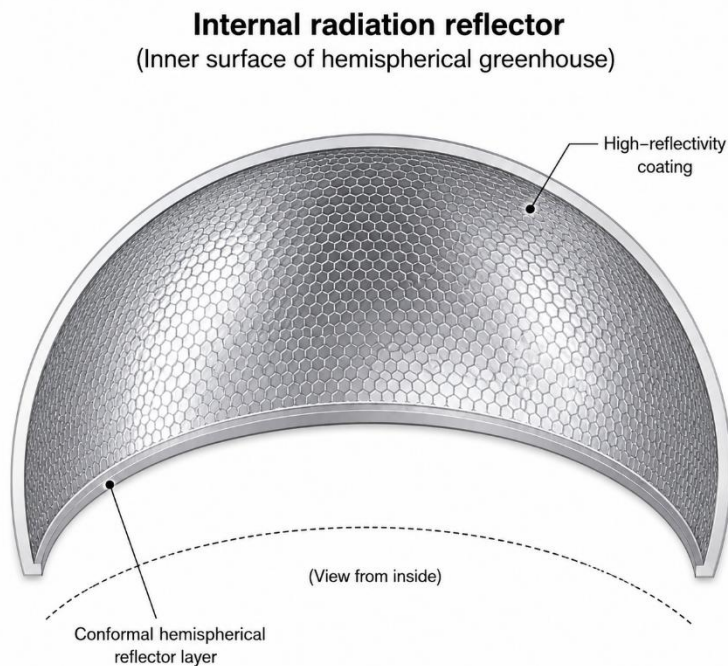


Figure 3. Internal radiation reflector developed for passive solar radiation recovery inside the hemispherical solar greenhouse

The internal radiation reflector was positioned along the inner peripheral surface of the hemispherical greenhouse surrounding the heat transfer medium. The reflector was designed to redirect the transmitted solar radiation towards the CNT–TiC coated photothermal surface, thereby increasing the interaction of solar radiation with the absorber and improving heat accumulation inside the greenhouse [17]. The thermal behaviour of the integrated system was investigated under three operating conditions, namely stagnation, natural convection, and operating conditions. The principal experimental operating conditions and coating preparation parameters adopted during the present investigation are summarized in Table 1.

Table 1. Experimental operating conditions and coating preparation parameters

Parameter	Value
Coating composition	CNT–TiC (70:30 wt%)
Coating thickness	$18 \pm 2 \mu\text{m}$
Spray coating rate	10 mL min^{-1}

Spray distance	15 cm
Carrier gas	Compressed air
Curing temperature	120 °C
Curing duration	1 h
Experimental duration	09:00–15:00 h
Air mass flow rate (operative condition)	0.02 kg s ⁻¹
Experimental configurations	Without reflector / With reflector

During the experiments, the temperatures of the heat transfer medium and the greenhouse air were recorded at regular time intervals. Simultaneously, the incident solar radiation, ambient temperature, and wind speed were monitored using calibrated instruments. The thermal response of the greenhouse was evaluated for two configurations: (i) CNT–TiC coated heat transfer medium without an internal radiation reflector and (ii) CNT–TiC coated heat transfer medium with an internal radiation reflector. The recorded thermal data were used to evaluate the influence of the internal radiation reflector on temperature distribution, heat accumulation, and overall thermal behaviour of the hemispherical solar greenhouse under identical outdoor operating conditions.

2.5 Thermal performance evaluation

The thermal performance of the hemispherical solar greenhouse was evaluated based on the useful heat gain and thermal efficiency of the system. The useful heat gain obtained from the heat transfer medium was calculated by considering the mass flow rate, specific heat capacity, and temperature difference between the inlet and outlet of the working medium. The thermal efficiency was determined from the ratio of useful heat gain to the incident solar energy received by the greenhouse aperture area. The governing equations used for calculating the useful heat gain and thermal efficiency are given below: [17,18]

$$Q_u = \dot{m} \cdot C_p (T_o - T_i) \quad (3)$$

The heat loss from the hemispherical solar greenhouse was estimated as the difference between the total incident solar energy and the useful heat gain, as expressed in Eq. (4) [17]

$$Q_{\text{loss}} = Q_{\text{solar}} - Q_u \quad (4)$$

Where Q_u is the useful heat gain (W), $\dot{m}$ is the mass flow rate of air (kg s^{-1}), Q_{loss} is the heat loss (W), Q_{solar} is the total incident solar energy (W). C_p is the specific heat capacity of air at constant pressure ($\text{J kg}^{-1} \text{K}^{-1}$), T_o and T_i denote the outlet and inlet air temperatures (K), respectively.

The thermal efficiency of a solar collector is commonly determined using [18]

$$\eta_{\text{Th}} = \frac{Q_u}{I A_c} \quad (5)$$

Where η_{Th} represents the collector thermal efficiency, I is the incident solar irradiance (W/m^2), A_c is represents the collector area (m^2).

The performance improvement obtained through the CNT–TiC coating and internal reflector integration was analyzed by comparing the thermal response of different experimental configurations. The calculated thermal parameters were used to compare the influence of CNT–TiC coating and internal reflector integration on the performance of the hemispherical solar greenhouse.

2.6. Experimental repeatability and uncertainty analysis

The outdoor thermal experiments were repeated under similar meteorological conditions to evaluate the repeatability of the developed system. The recorded temperatures and thermal performance parameters were averaged from repeated measurements and are presented as mean values with standard deviation. The variations observed during repeated experiments were considered while analyzing the thermal response of the coated heat transfer medium and the hemispherical solar greenhouse. The experimental instruments used for thermal performance evaluation and their measurement specifications are summarized in Table 2.

Table 2. Experimental instruments used for thermal performance evaluation

Instrument	Measured parameter	Measurement range	Accuracy
Pyranometer	Solar radiation	0–2000 W m^{-2}	$\pm 2.0\%$
Platinum resistance thermometer	Temperature	0–100 $^{\circ}\text{C}$	$\pm 1.0\%$
Cup anemometer	Wind speed	0–30 m s^{-1}	$\pm 1.5\%$

Rotameter	Air mass flow rate	0–1 kg s ⁻¹	±2.5%
Digital data logger	Temperature acquisition	Multi-channel	±0.5 °C

The measurement uncertainties associated with the experimental instruments were considered throughout the investigation. The experiments were repeated three times under similar outdoor conditions, and the results are presented as mean ± standard deviation. The uncertainties were ±2.0% for solar radiation, ±1.0% for temperature measurement, ±1.5% for wind speed, and ±2.5% for mass flow rate. Based on these measurement uncertainties, the overall uncertainties of the calculated useful heat gain, thermal efficiency, and Photothermal Temperature Contribution (PTTC) index were estimated using the standard uncertainty propagation method and found to be within ±3.8%, ±4.2%, and ±2.9%, respectively, confirming the reliability of the reported thermal performance.

3. Results and discussion

3.1. Structural, morphological and optical characterization of the CNT–TiC coating

The XRD pattern of the synthesized CNT–TiC nanocomposite powder is shown in Figure 4. The characteristic diffraction peaks corresponding to crystalline carbon nanotube (CNT) and titanium carbide (TiC) confirmed the successful formation of the nanocomposite without detectable secondary or impurity phases. The absence of secondary phases indicates the successful synthesis of the CNT–TiC nanocomposite powder. The average crystallite size calculated using the Debye–Scherrer equation was 53 nm, suggesting the formation of fine crystallites with a large effective surface area, which is favourable for efficient solar energy absorption and thermal transport. The combined presence of CNT and TiC is expected to facilitate improved photothermal conversion because of their complementary optical absorption and heat transfer characteristics. [6,19]

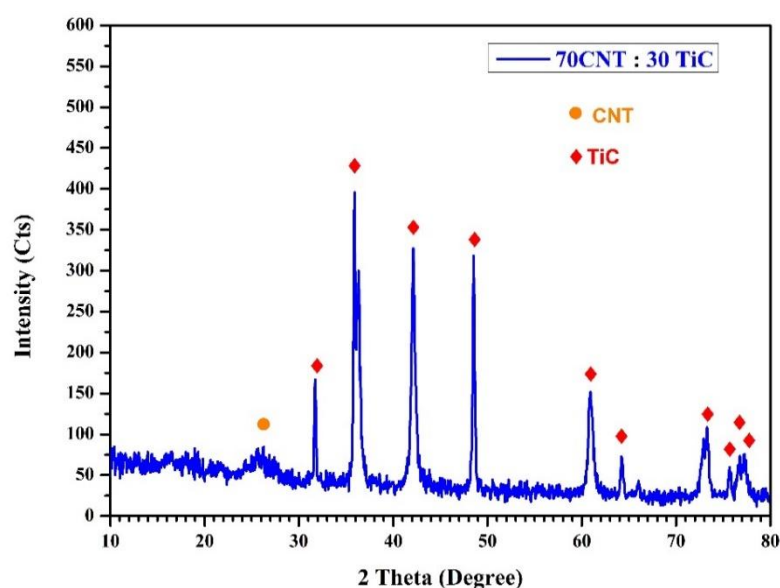


Figure 4. XRD diffractogram of CNT and nano TiC

The SEM micrograph presented in Figure 5 shows a compact, homogeneous, and uniformly distributed coating without visible cracks or peeling. The CNT network was well integrated with the TiC particles, producing a rough microstructure that enhances multiple light reflections and improves solar absorption. The uniform morphology also indicates good coating adhesion after spray deposition and curing. Such an interconnected microstructure facilitates effective heat distribution across the coated surface while minimizing localized thermal gradients, thereby improving the thermal response of the solar absorber coating. Similar surface morphologies have been reported to enhance the photothermal performance of carbon-based nanocomposite coatings [16,20].

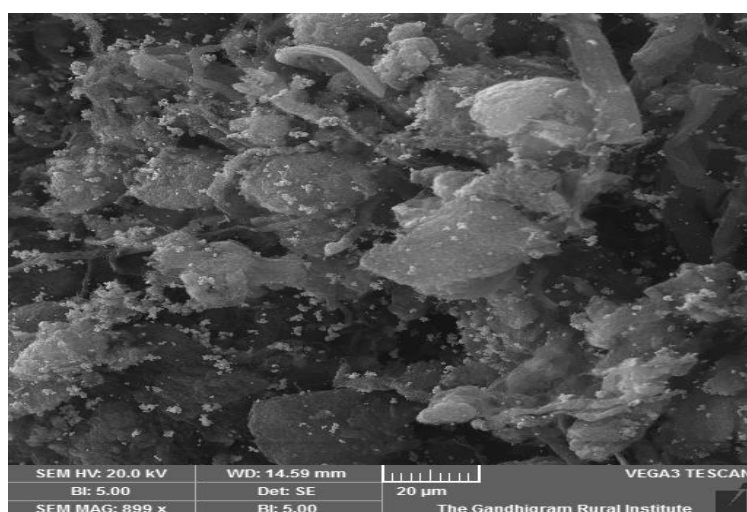


Figure 5. SEM image of CNT and nano TiC

The UV–Visible absorption spectrum of the synthesized CNT–TiC nanocomposite powder shown in Figure 6 exhibited strong optical absorption throughout the investigated UV and visible wavelength regions, with an absorption edge observed approximately between 320 and 380 nm. The broad optical absorption behaviour indicates the capability of the synthesized CNT–TiC nanocomposite powder to effectively harvest incident solar radiation over a wide spectral range. The combined structural, morphological, and optical characteristics confirm that the synthesized CNT–TiC nanocomposite powder possesses favourable optical properties for subsequent photothermal coating applications. The strong optical absorption observed in the visible region is consistent with previous studies on carbon-based photothermal nanocomposite coatings [19,21].

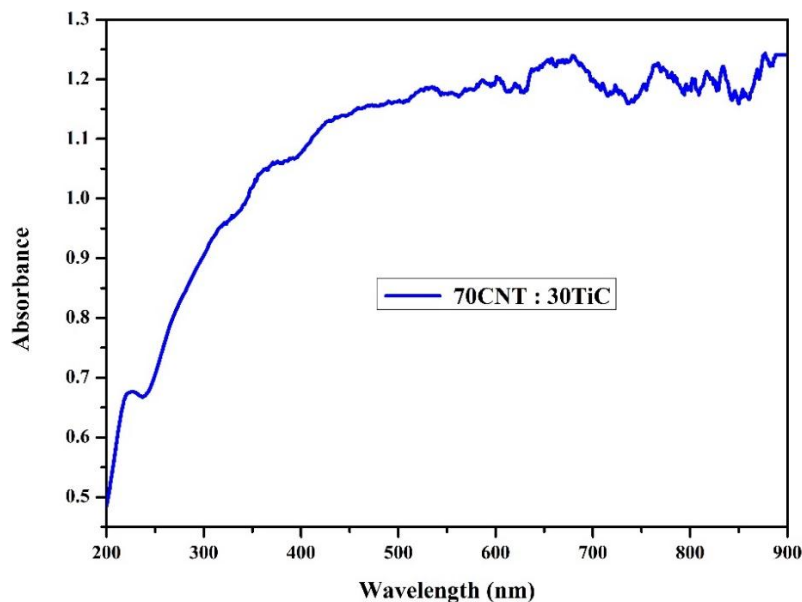


Figure 6. UV absorbance spectra of CNT and nano TiC

3.2. Outdoor thermal response of the CNT–TiC coated heat transfer medium

The outdoor thermal response of the CNT–TiC coated heat transfer medium was evaluated under identical atmospheric conditions and compared with the non-coated surface. The variation in solar radiation and ambient temperature during the experimental period is presented in Fig. 7, while the corresponding surface temperature profiles are shown in Fig. 8. The coated heat transfer medium consistently attained a higher temperature than the non-coated surface throughout the experiment, reaching a maximum temperature of 61.5 °C, whereas the non-coated surface reached 51.2 °C.

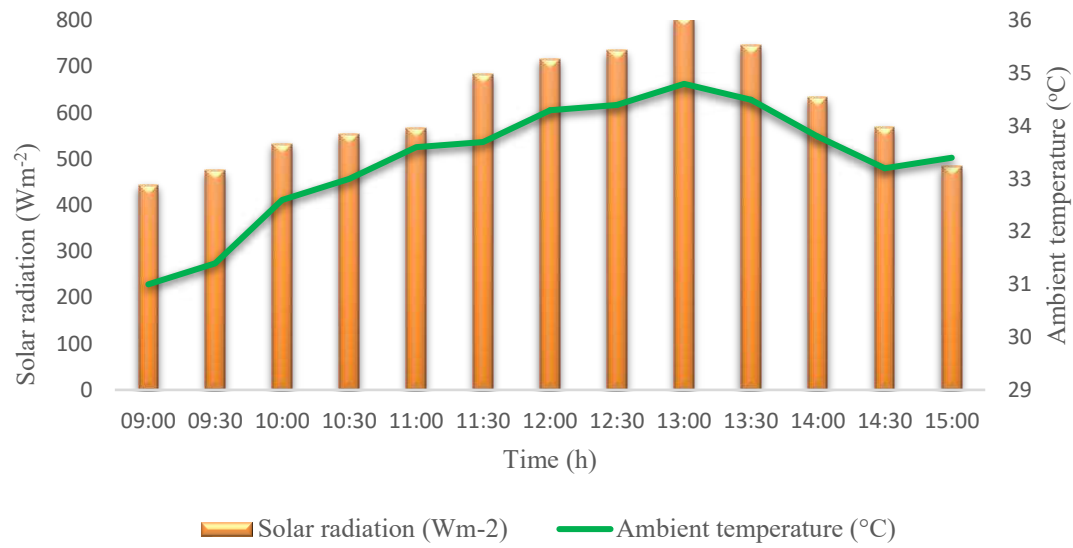


Figure 7. Temporal variation of average solar irradiance and ambient temperature during the outdoor thermal performance evaluation

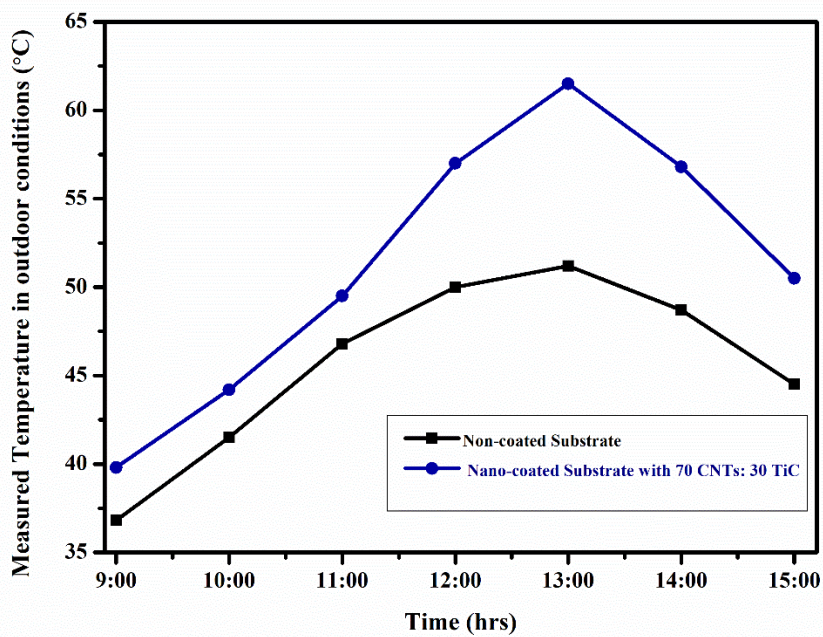


Figure 8. Temporal variation of the average surface temperature of non-coated and CNT-TiC nano-coated heat transfer media under outdoor exposure.

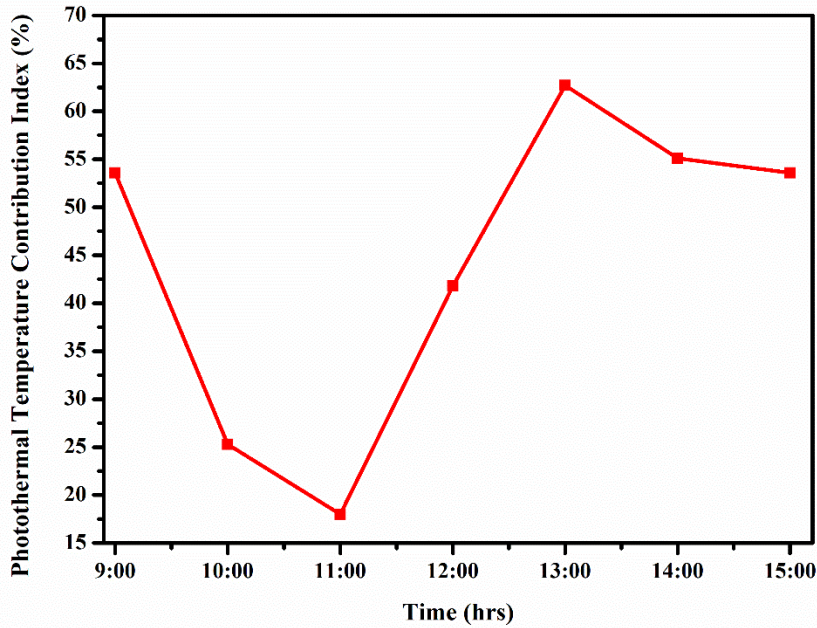


Figure 9. Temporal variation of the Photothermal Temperature Contribution (PTTC) index during the outdoor experimental period.

The improved thermal response is attributed to the enhanced photothermal characteristics of the CNT–TiC nanocomposite coating. The broad optical absorption of CNT together with the thermal stability of TiC promoted efficient conversion of solar radiation into heat. The corresponding PTTC values shown in Fig. 9 reached a maximum of 62.7%, confirming the positive contribution of the developed coating under identical outdoor conditions. The temperature difference between the coated and non-coated surfaces became more pronounced during periods of high solar irradiance, confirming that the developed coating effectively responds to variations in solar intensity. Similar behaviour has been reported for carbon-based photothermal coatings used in solar thermal systems [22,23]. These results indicate that the developed coating provides an effective photothermal surface before its integration into the hemispherical solar greenhouse.

3.3. Thermal response of the hemispherical solar greenhouse

The thermal response of the hemispherical solar greenhouse with and without the internal radiation reflector is presented in Figs. 10–13. Under stagnation, natural convection, and operative conditions, the greenhouse integrated with the internal radiation reflector consistently maintained higher temperatures than the conventional configuration. Under stagnation

conditions, the maximum average greenhouse air temperature increased from 55.0 °C to 58.7 °C, while the maximum heat transfer medium surface temperature increased from 73.8 °C to 78.4 °C after incorporating the internal radiation reflector.

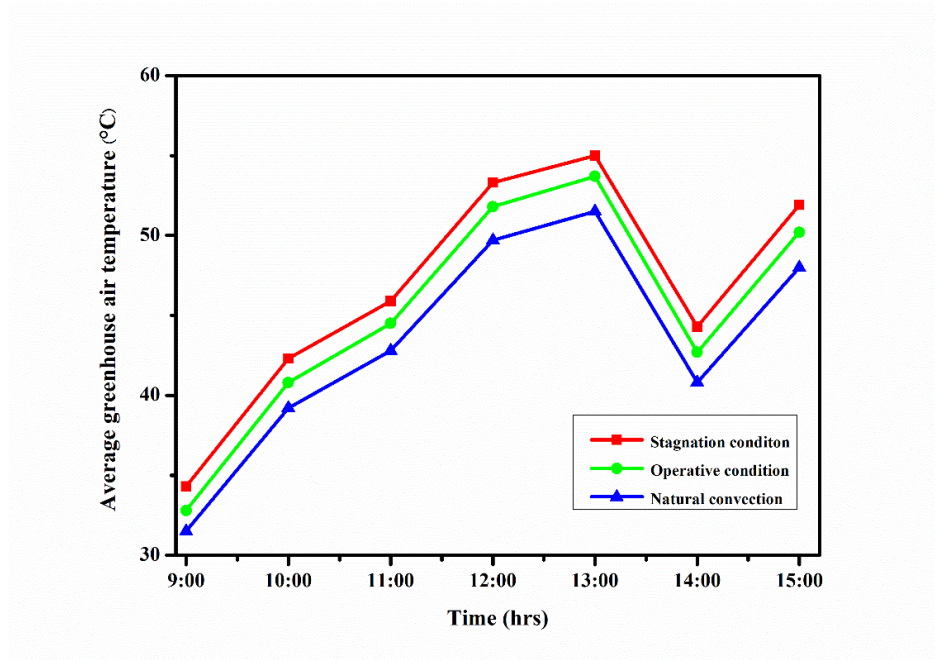


Figure 10. Average greenhouse air temperature under different operating conditions without the internal radiation reflector

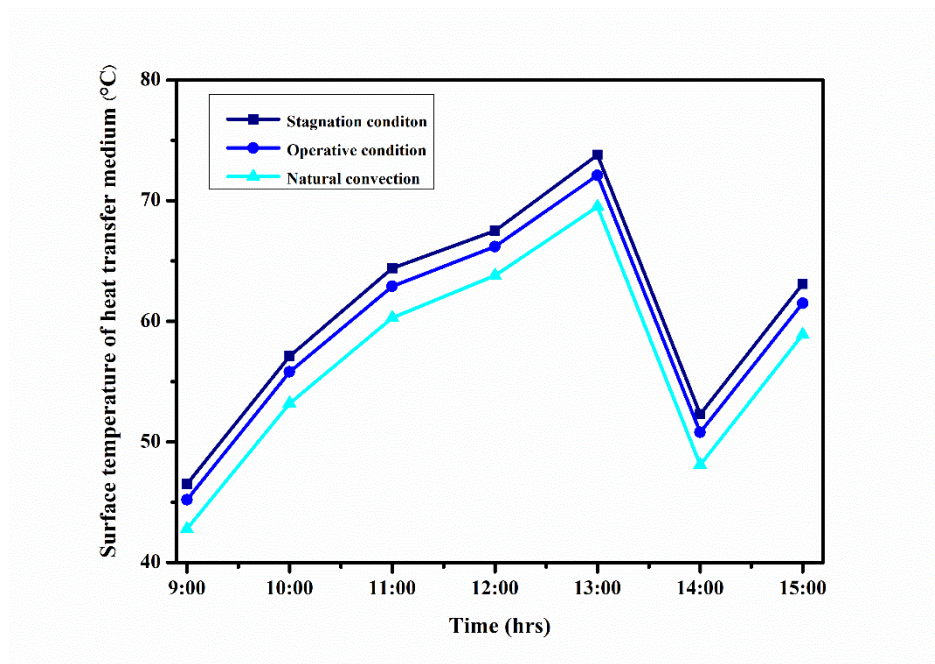


Figure 11. Surface temperature of the heat transfer medium under different operating conditions without the internal radiation reflector

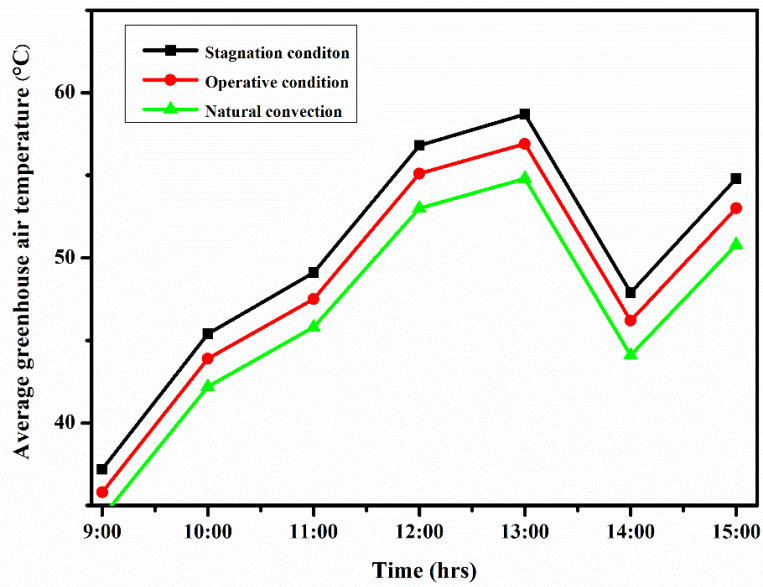


Figure 12. Average greenhouse air temperature under different operating conditions with internal radiation reflector

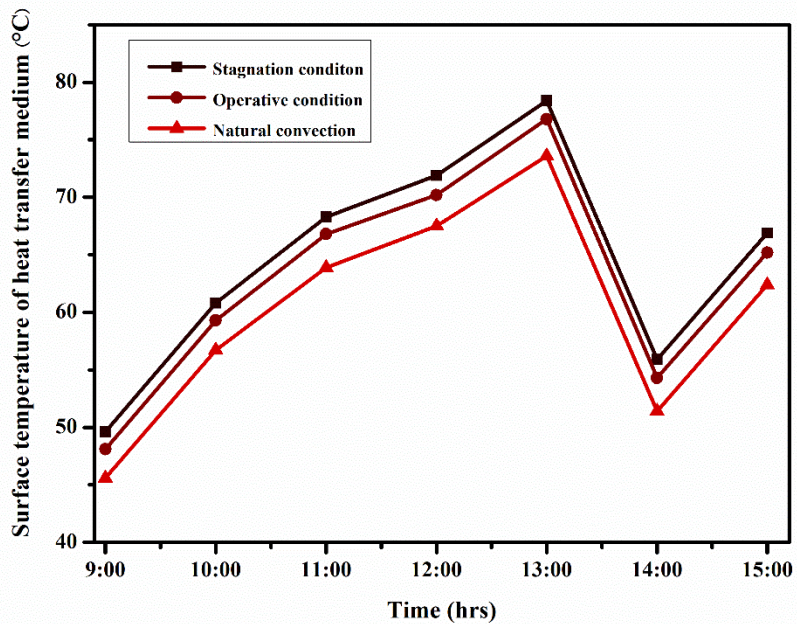


Figure 13. Surface temperature of the heat transfer medium under different operating conditions with internal radiation reflector

The improved thermal response is attributed to the combined effect of the CNT–TiC photothermal coating and the internal radiation reflector. The reflector redirected transmitted solar radiation towards the coated heat transfer medium, increasing the interaction between the absorber surface and incident radiation [24]. This enhanced heat accumulation within the enclosure and reduced radiation losses, resulting in improved thermal performance under all operating conditions. The stable temperature profile reveals that the reflector effectively improves solar energy utilization without modifying the greenhouse geometry.

The improvement was consistently observed throughout the experimental period, indicating that the reflector contributed to sustained heat retention rather than only increasing the peak temperature. This stable thermal behaviour is desirable for continuous greenhouse operation under fluctuating environmental conditions [16].

3.4. Effect of the internal radiation reflector on thermal performance

The effect of the internal radiation reflector on the thermal performance of the hemispherical solar greenhouse is presented in Figures 14 to 17. The incorporation of the reflector increased the useful heat gain while reducing the overall heat loss under identical outdoor conditions. Consequently, the greenhouse integrated with the reflector exhibited a higher thermal efficiency than the conventional configuration.

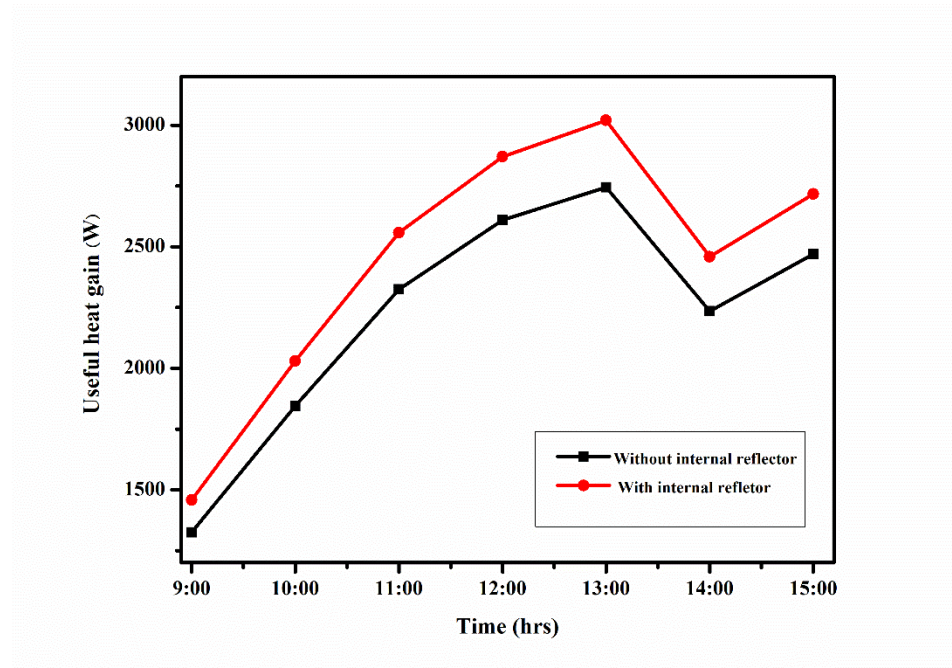


Figure 14. Variation in useful heat gain of the hemispherical solar greenhouse with and without the internal radiation reflector under outdoor operating conditions.

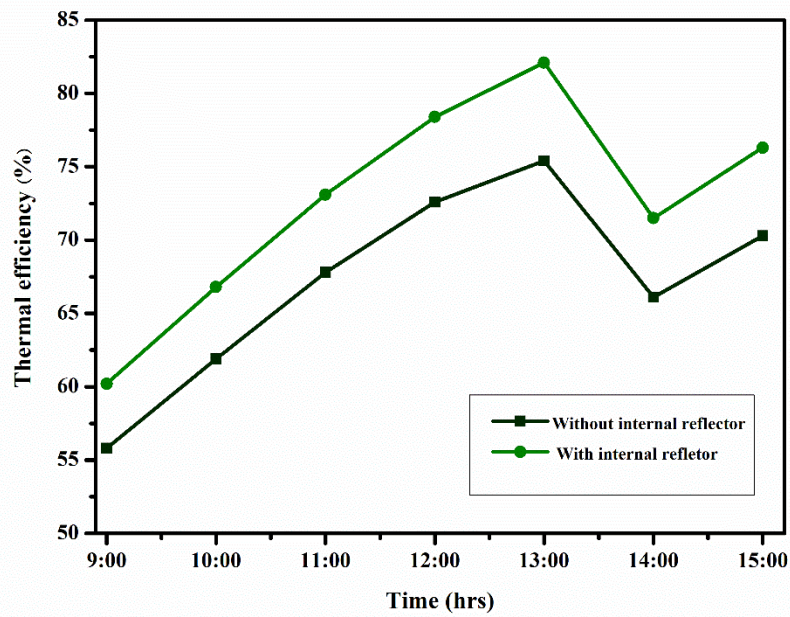


Figure 15. Variation in the thermal efficiency of the hemispherical solar greenhouse with and without the internal radiation reflector under outdoor operating conditions.

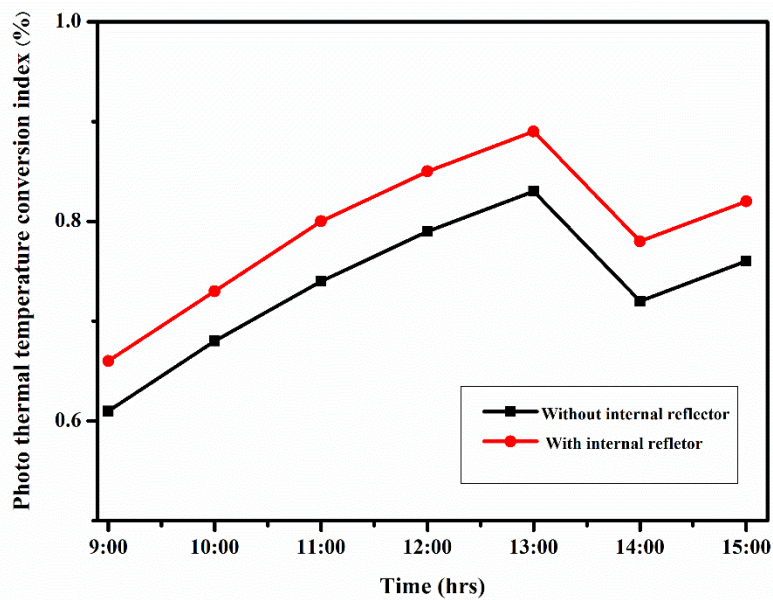


Figure 16. Variation of the photothermal temperature contribution (PTTC) index with and without the internal radiation reflector under outdoor operating conditions.

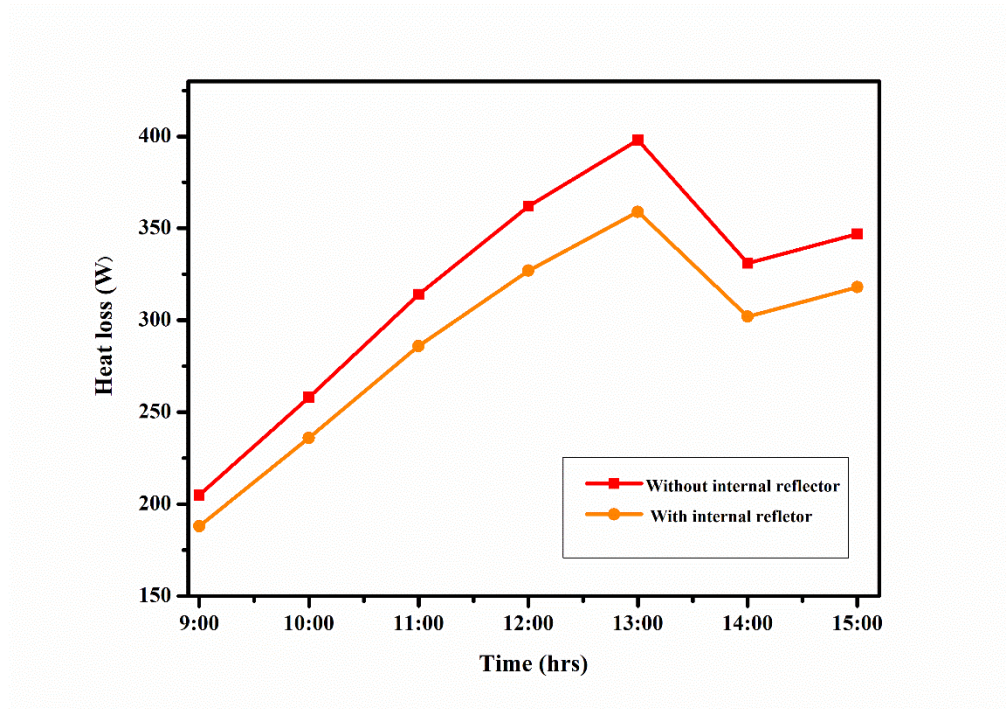


Figure 17. Variation in heat loss of the hemispherical solar greenhouse with and without the internal radiation reflector under outdoor operating conditions.

The useful heat gain increased from 2745 W to 3020 W, whereas the heat loss decreased from 398 W to 359 W after incorporating the internal radiation reflector. The maximum thermal efficiency also improved from 75.4% to 82.1%, demonstrating more effective utilization of the available solar energy. This improvement is attributed to the redirection of transmitted solar radiation towards the CNT–TiC coated heat transfer medium, which increased heat absorption and reduced radiative energy losses [25]. The simultaneous increase in useful heat gain and reduction in heat loss demonstrate that the internal radiation reflector improved the overall energy utilization efficiency of the greenhouse. Unlike active thermal enhancement methods, the proposed reflector operates passively without additional power consumption, making it suitable for practical solar greenhouse applications. The combined action of the photothermal coating and internal radiation reflector therefore enhanced the overall thermal performance of the hemispherical solar greenhouse.

3.5. Thermal performance comparison with reported systems

A comparison between the present study and representative solar thermal systems reported in the literature is presented in Table 3. Although different absorber materials, greenhouse configurations, and operating conditions have been employed, the proposed CNT–TiC coated

hemispherical solar greenhouse integrated with an internal radiation reflector demonstrated competitive thermal performance.

Table 3. Comparison of the present hemispherical solar greenhouse with previously reported solar thermal systems

Study	Coating / Material	Greenhouse / Dryer	Max Temp (°C)	Thermal Efficiency (%)	Improvement	Reference
Triple-flow greenhouse dryer with CuO nano absorber coating (2022)	CuO nano coating	Even-span greenhouse dryer	~60.0	70.4–75.1	Nano coating improved thermal performance	[27]
Graphene nanoplatelet-coated solar greenhouse dryer (2022)	Graphene nanoplatelet (GNP) coating	Single-slope greenhouse dryer	~64.0	74.6	Enhanced solar heat absorption and reduced drying time	[5]
Indirect solar greenhouse dryer using helical fin (2024)	Helical fin solar air heater	Indirect greenhouse dryer	—	61.3	Enhanced heat transfer and greenhouse thermal performance	[28]
CNT–nano SiC coated half-cylindrical greenhouse dryer (2026)	CNT–SiC	Half-cylindrical greenhouse	59.7	77.8	Nano coating enhanced greenhouse temperature	[22]
Present work	CNT–TiC + Internal radiation reflector	Hemispherical greenhouse	78.4	82.1	Highest thermal efficiency through reflector-assisted heat recovery	—

The improvement is attributed to the combined effect of enhanced photothermal conversion by the CNT–TiC coating and internal recovery of transmitted solar radiation. Although direct comparison is influenced by differences in greenhouse geometry, climatic conditions, and operating parameters, the present system demonstrated competitive thermal performance using a simple passive modification. The combined material and system design therefore offers an effective approach for improving low-temperature solar thermal technologies. The proposed material–system approach improves solar energy utilization without increasing the collector

area or requiring additional energy input, demonstrating its potential for efficient low-temperature solar thermal applications.

4. Conclusions

A CNT–TiC nanocomposite photothermal coating integrated with an internal radiation reflector was successfully developed to enhance the thermal performance of a hemispherical solar greenhouse. Structural, morphological, and optical characterization confirmed the successful formation of a uniform photothermal coating suitable for solar thermal applications. Under identical outdoor conditions, the coated heat transfer medium attained a maximum temperature of 78.4 °C with a Photothermal Temperature Contribution (PTTC) index of 89.7 %, confirming the effectiveness of the developed coating. After greenhouse integration, the useful heat gain increased from 2745 W to 3020 W, the heat loss decreased from 398 W to 359 W, and the thermal efficiency improved from 75.4% to 82.1% following the incorporation of the internal radiation reflector. The combined action of the CNT–TiC coating and passive radiation recovery enabled improved solar energy utilization without increasing the collector area or requiring external energy input. The proposed material–system approach offers a simple and effective strategy for improving the thermal performance of solar greenhouses and other low-temperature solar thermal systems. Future studies should focus on long-term outdoor durability, large-scale coating deposition, and seasonal performance evaluation under different climatic conditions.

Credit authorship contribution statement

R. Ranjith carried out the conceptualization, methodology, investigation, formal analysis, data curation, visualization, and preparation of the original manuscript. P.J. Jegan Babu contributed to supervision, methodology, validation, manuscript review, and critical revision of the manuscript. R.V. Jeba Rajasekhar contributed to supervision, project administration, resource management, manuscript review, and overall guidance throughout the study. All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Statement on the Use of Generative Artificial Intelligence (AI):

The author(s) acknowledge the use of ChatGPT (GPT-5), a large language model developed by OpenAI, exclusively for grammar checking, language refinement, and improvement of clarity in the manuscript. The tool was not employed for data analysis, interpretation, or the generation of substantive scientific content. All conceptualization, methodology, and conclusions presented in this work are entirely those of the author(s).

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