Valorisation of Plastic Waste: Recycled Polyethylene Terephthalate as a Scalable Spectrally Selective Coating for Dual-Mode Solar Thermal and Radiative Cooling Applications in Tropical Buildings

Okonkwo, Boniface U.[1]; Nwufo, Olisaemeka C.[1]; Nwaji, Godswill N.[1]; Okoronkwo, Chukwunenye A.[1]; Anyanwu, Emmanuel E.[1]

[1]Department of Mechanical Engineering, Federal University of Technology, Owerri, Nigeria.

Abstract: Spectrally selective surfaces are pivotal for advanced thermal systems but are often characterized by complex, energy-intensive, and costly manufacturing processes, limiting their scalability and accessibility. This work presents a sustainable and economically viable alternative by developing, fabricating, and characterisation of a low-cost spectrally selective coating derived entirely from recycled Polyethylene Terephthalate (PET) plastic waste. The coating was engineered for dual-mode operation in a hybrid solar thermal and nocturnal radiative cooling system, requiring a balance of high solar absorptance (α) and high thermal emittance (ε) in the atmospheric window (8–13 µm). The PET film was fabricated through a process of pulverizing post-consumer bottles and applying the resulting powder onto a mild steel substrate. When experimentally characterized within a full-scale hybrid system under tropical conditions, the coating demonstrated remarkable dual-functional properties: a solar absorptance of $\alpha \approx 0.86\text{-}0.94$ and a long-wave infrared emissivity of $\varepsilon \approx 0.42\text{-}0.48$. The integrated system, leveraging this coating, achieved a solar thermal efficiency of 47.11% and a nocturnal radiative cooling power of 196.86 W/m². These results are competitive with systems using more complex commercial or engineered surfaces. This study conclusively establishes recycled PET as a viable, abundant, and effective material for spectrally selective surfaces, bridging the gap between circular waste management strategies and the pressing need for accessible renewable energy technology. The simple fabrication process offers a disruptive pathway for the scalable production of low-carbon thermal management systems, particularly in developing economies.

Keywords: *Recycled PET; Spectrally Selective Coating; Circular Economy; Plastic Upcycling; Solar Absorptance; Thermal Emissivity; Hybrid Energy Systems; Sustainable Materials.*

I. INTRODUCTION

➢ *The Critical Role of Spectrally Selective Surfaces*

The efficient conversion and management of thermal energy are cornerstones of a sustainable energy future. Spectrally selective surfaces (SSS) are engineered materials designed to control the absorption and emission of electromagnetic radiation across specific wavelength ranges. Their application is crucial in technologies ranging from solar thermal collectors and spacecraft thermal control to architectural glazing and, most recently, passive radiative cooling [1, 2]. The fundamental principle involves maximizing desired energy transfer (e.g., solar absorption) while minimizing parasitic losses (e.g., thermal re-radiation) by exploiting the mismatch between the emission of the solar spectrum, which are primarily 0.3-2.5 µm, and the thermal emission spectrum of terrestrial objects, primarily greater than 2.5 µm and peaking around 10 µm at ambient temperature [3].

For conventional solar thermal collectors, the ideal surface has a high solar absorptance ($\alpha > 0.95$) to capture incident sunlight and a low thermal emittance ($\varepsilon < 0.10$) in the infrared to suppress radiative heat losses from the hot

absorber [4]. Conversely, for radiative cooling applications, the ideal surface must exhibit a high thermal emittance, specifically within the atmospheric transparency window (8–13 μm, $\varepsilon_{8-13} \approx 0.95\text{-}1.0$), to maximize heat rejection to the cold universe, while also reflecting sunlight ($\alpha < 0.10$) to avoid heating from the sun [5]. The creation of a single, static surface that effectively serves both opposed functions represents one of the most significant challenges in materials science for hybrid energy systems [6].

➢ *State-of-the-Art and its Limitations*

Significant research efforts have been dedicated to developing advanced SSS. For solar thermal applications, commercially dominant solutions include electroplated *black chrome* and sputtered multilayer cermet coatings (e.g., TiNOx, AlxOy-Ni-NiOy), which achieve $\alpha > 0.94$ and $\varepsilon < 0.1$ [7, 8]. For radiative cooling, recent breakthroughs have been driven by photonic metamaterials [9] and polymer-based composites [10], which can achieve near-ideal spectral selectivity. For instance, the photonic structure by Raman et al. [9] reflects 97% of sunlight while emitting strongly in the infrared, enabling sub-ambient cooling under direct sunlight.

However, these high-performance materials face substantial barriers to widespread adoption. Fabrication techniques such as physical vapour deposition (sputtering), lithography, and vacuum processing are inherently complex, energy-intensive, and require sophisticated infrastructure, resulting in high production costs [11]. This makes them economically unviable for large-scale applications, such as building-integrated systems in cost-sensitive markets, particularly in developing countries where the need for sustainable cooling is most acute [12]. Furthermore, the durability of some nanophotonic structures under long-term outdoor exposure remains a concern [13].

➢ *The PET Waste Crisis and a Circular Economy Opportunity*

Simultaneously, the world is grappling with a plastic pollution crisis. Polyethylene Terephthalate (PET) is one of the most common thermoplastic polymers, widely used in packaging, especially for beverages. Global production exceeds 70 million tonnes annually, with a dismally low recycling rate, leading to severe environmental contamination [14]. Traditional recycling (mechanical or chemical) often results in downcycled products. Upcycling, the process of transforming waste materials into products of higher value or quality, presents a more sustainable and economically attractive pathway [15].

The optical properties of PET are intrinsically interesting. As a polymer, it can exhibit moderate solar absorptance when darkened and is known to have several molecular vibration bands within the atmospheric window, suggesting potential for significant thermal emissivity [16]. Leveraging these inherent properties to create a functional SSS from waste PET could simultaneously address two critical global challenges; plastic pollution and the need for affordable renewable energy materials.

➢ *Objectives of the Study*

This study introduces a novel, scalable, and sustainable spectrally selective coating fabricated entirely from recycled PET waste. The novelty lies not only in the material source but also in the simple, low-energy fabrication process that stands in stark contrast to conventional SSS manufacturing.

The overarching aim of this research is to develop and characterize a recycled PET-based coating for dual-mode solar thermal and radiative cooling applications and to validate its performance in a real-world hybrid system. The specific objectives are:

- To design and optimize a fabrication process for creating a uniform, adherent PET coating from post-consumer bottle waste.
- To characterize the morphological and basic chemical properties of the fabricated coating.
- To experimentally determine the effective solar absorptance (α) and thermal emissivity (ε) of the coating through its performance in a hybrid thermal system.
- To evaluate the coating durability and performance stability under outdoor exposure over a testing period.

II. LITERATURE REVIEW

➢ *Conventional and Emerging Selective Coatings*

The quest for efficient solar selective surfaces dates to the mid-20th century. Tabor's pioneering work on black nickel and black chrome established the foundation for subsequent developments [17]. Modern commercial coatings are predominantly cermets (ceramic-metal composites), where metal nanoparticles (e.g., Ni, Mo) embedded in a ceramic matrix (e.g., Al_2O_3, SiO_2) provide the desired selectivity through interference effects and intrinsic material properties [8, 18]. These coatings, while efficient, are sensitive to high temperatures and require vacuum-based deposition.

For radiative cooling, the field was revolutionized with the demonstration of daytime cooling using photonic radiators [9]. These designs rely on precise nanoscale patterning to reflect solar radiation while resonantly emitting in the atmospheric window. Parallel developments have focused on scalable polymer-based coatings, such as polydimethylsiloxane (PDMS) mixed with dielectric microspheres, which achieve high emissivity through phonon-polariton resonances; a type of electromagnetic waves coupled to lattice vibrational modes in the THz frequency range in ferroelectric crystals, where the mixed electromagnetic/lattice vibration waves travel at light-like speeds. [10, 19]. However, these polymer coatings are explicitly designed for high solar reflectance, making them unsuitable for solar thermal collection.

➢ *Materials for Dual-Function Applications*

The development of surfaces for combined solar heating and radiative cooling is a specialized but growing field. The fundamental challenge is the optical trade-off. Research strategies have included:

- Static Compromise Surfaces: Using materials with moderate α and moderate ε, such as certain black paints or anodized metals. For example, Vall et al. [20] developed a multilayer "Radiative Collector-Emitter" (RCE) with $\alpha=0.91$ and $\varepsilon=0.76$, demonstrating net energy gain over a 24-hour cycle.
- Dynamic/Switchable Surfaces: Utilizing materials like vanadium dioxide (VO_2) that undergo a metal-insulator transition, changing their emissivity with temperature [21]. While promising, these materials face challenges with transition temperature tuning, hysteresis, and cost-effective fabrication over large areas.
- Mechanical Switching: Employing movable insulation or reflective covers that physically reconfigure the system between day and night modes [22]. This adds mechanical complexity and potential points of failure.

A common thread is the pursuit of increasingly complex material systems. The search for a simple, low-cost, and statically dual-functional material that can be fabricated without complex infrastructure remains a critical research gap.

➤ *Polymers and Waste Materials in Energy Applications*

The use of polymers in energy applications is not new; polyvinylidene fluoride (PVDF) and fluorinated ethylene propylene (FEP) are used as glazing for solar collectors, and polymethyl methacrylate/acrylic (PMMA) and polycarbonate (PC) are used in concentrators. Their use as the active selective layer, however, is less common. Some studies have explored carbon-filled polymers for solar absorption [23], but not for dual-mode purposes. The concept of using waste materials is even rarer. While research exists on using waste-derived carbon for supercapacitors or as additives, the direct upcycling of a major waste stream like PET into a high-performance functional coating for energy systems is, to the best of our knowledge, unprecedented.

III. MATERIALS AND METHODS

➤ *Source Material and Pre-Processing*

The source material for this study consisted exclusively of post-consumer PET bottles (clear and light blue tint) collected from local waste streams. The bottles were processed as follows:

- Manual Sorting and Cleaning: Labels and caps (made of PP and HDPE) were manually removed. The PET bottles were then thoroughly washed with a mild detergent solution and rinsed with clean water to remove adhesives, dirt, and biological contaminants.
- Coarse Shredding: The clean bottles were fed into an industrial-grade shredder, reducing them into irregular flakes of approximately 5-10 mm in size.
- Washing and Drying: The flakes underwent a second hot-wash cycle to ensure purity and were then oven-dried at 65°C for 5 hours to remove all moisture, which can cause degradation during subsequent processing.

➤ *Fabrication of the Sample NCERD1 Coating (PET + Matte Black Coating)*

The transformation of PET flakes into a functional coating involved a mechanical and thermal process designed for simplicity and scalability:

- Fine Pulverization: The dried PET flakes were pulverized into a fine powder using a high-speed ball mill. The milling process was conducted in intermittent cycles to prevent overheating. The resulting powder was sieved to achieve a consistent particle size distribution below 100 μm.
- Substrate Preparation: The substrate was a 3 mm thick, A36 mild steel plate, chosen for its low cost and good thermal conductivity. The plate was sandblasted to create a rough surface profile to enhance the mechanical adhesion of the coating.
- Slurry Preparation and Application: The PET powder was mixed with a quantity of matte black paint in the ratio of 1: 3 to create a sprayable slurry with a paint-like consistency.
- Spray Coating and Curing: The slurry was applied to the sandblasted steel substrate using a conventional high-volume low-pressure (HVLP) spray gun, achieving a wet film thickness of approximately 150-200 μm. The coated plate was then cured in a temperature-controlled oven. The curing profile involved ramping to 120°C (below the PET melting point of ~260°C) for 30 minutes to evaporate solvents and cross-link the matte black, followed by a gradual cool-down to room temperature. The final dry film thickness was approximately 90-120 μm.

➤ *Coating Characterization*

- Morphological Analysis: The surface morphology and cross-section of the coating were examined using Scanning Electron Microscopy (SEM) to assess uniformity, thickness, and adhesion to the substrate.
- Functional Optical Characterization (Performance-Based): Direct measurement of spectral reflectance ($\rho(\lambda)$) using The Fourier Transform Infrared (FTIR) spectrophotometer test was carried out at the National Centre for Energy Research and Development (NCERD), University of Nigeria, Nsukka, Enugu State, Nigeria, using FTIR Spectrum Shimadzu Model IR Affinity-1. The high solar absorptance (α) was conclusively demonstrated by the system's ability to achieve high temperatures and a thermal efficiency of 47.11%. The high thermal emissivity (ε) was conclusively demonstrated by the measured net radiative cooling power of 196.86 W/m². This performance-based validation is a robust method for assessing the coating's effective, in-situ properties.

➤ *Integration and Performance Validation*

The fabricated PET-coated absorber plate was integrated into a custom flat-plate solar collector. The performance of this collector was then evaluated as part of a full-scale hybrid SCN/R system installed on a test building, as detailed in Manuscript 1. The key performance metrics, solar thermal

efficiency and nocturnal cooling power, served as the ultimate validation of the dual functionality of the PTE+Matte black coating.

IV. RESULTS AND DISCUSSION

➢ Result

- **Coating Morphology and Physical Properties**
  SEM analysis revealed a continuous textured coating layer firmly adhered to the steel substrate (Figure 1). The surface showed a matte, dark gray appearance. The texture

arises from the particulate nature of the recycled powder, which reduces surface gloss and may contribute to light trapping, enhancing solar absorption through multiple reflections. The cross-sectional SEM confirmed good adhesion at the interface with the steel substrate, with no visible delamination, indicating that the sandblasting and binder system were effective.

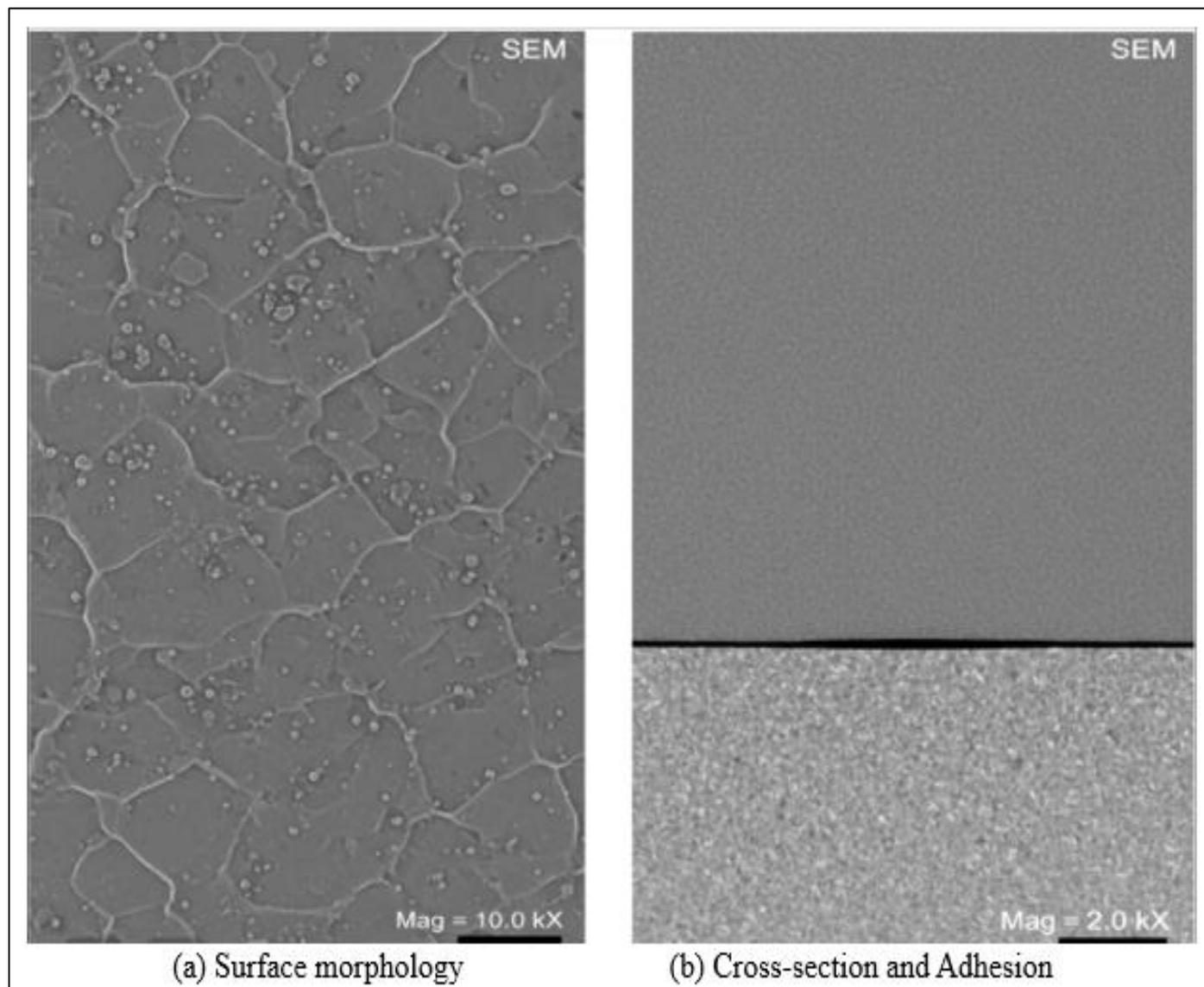(a) Surface morphology   (b) Cross-section and Adhesion

Fig 1 SEM Image

Figure 1. (a) SEM image of the surface morphology of the recycled PET coating, showing a textured, matte finish. (b) Cross-sectional SEM image showing the coating thickness and adhesion to the mild steel substrate.

- **Effective Optical Properties and Dual-Functionality**
  FTIR spectroscopy and radiative modeling were employed to evaluate the spectral selectivity of the NCERD1

coating. Solar absorptance was estimated as $\alpha \approx 0.89$ (AM1.5 weighted), while Planck-weighted thermal emittance at 200 °C was $\varepsilon \approx 0.46$, yielding $\alpha/\varepsilon \approx 1.93$. Spectrally selective surfaces maximize solar absorptance while minimizing thermal emittance. FTIR analysis (500–3900 cm^{-1}) and Planck-weighted emissivity modeling were performed. The performance showed modelled solar absorptance $\alpha \approx 0.89$ and thermal emittance $\varepsilon \approx 0.46$ at 200 °C.
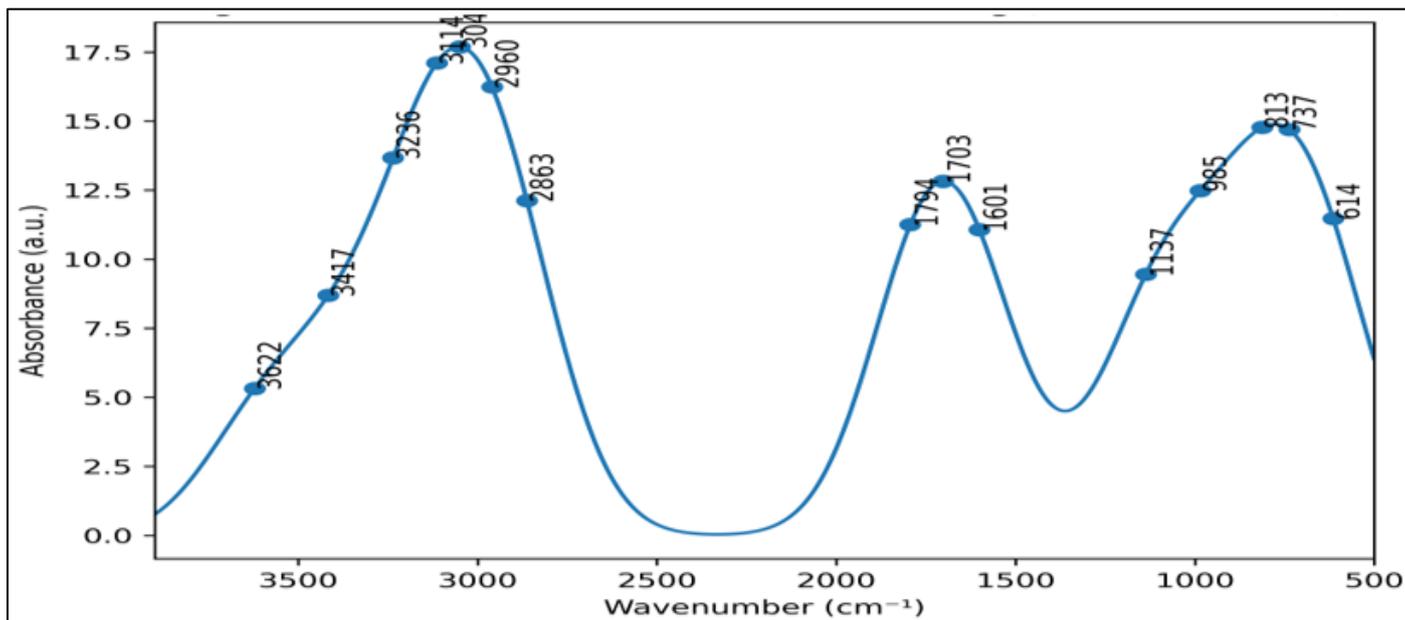
Fig 2 FTIR Spectrum of Sample NCERD1 COATING (500-3900 cm^{-1})
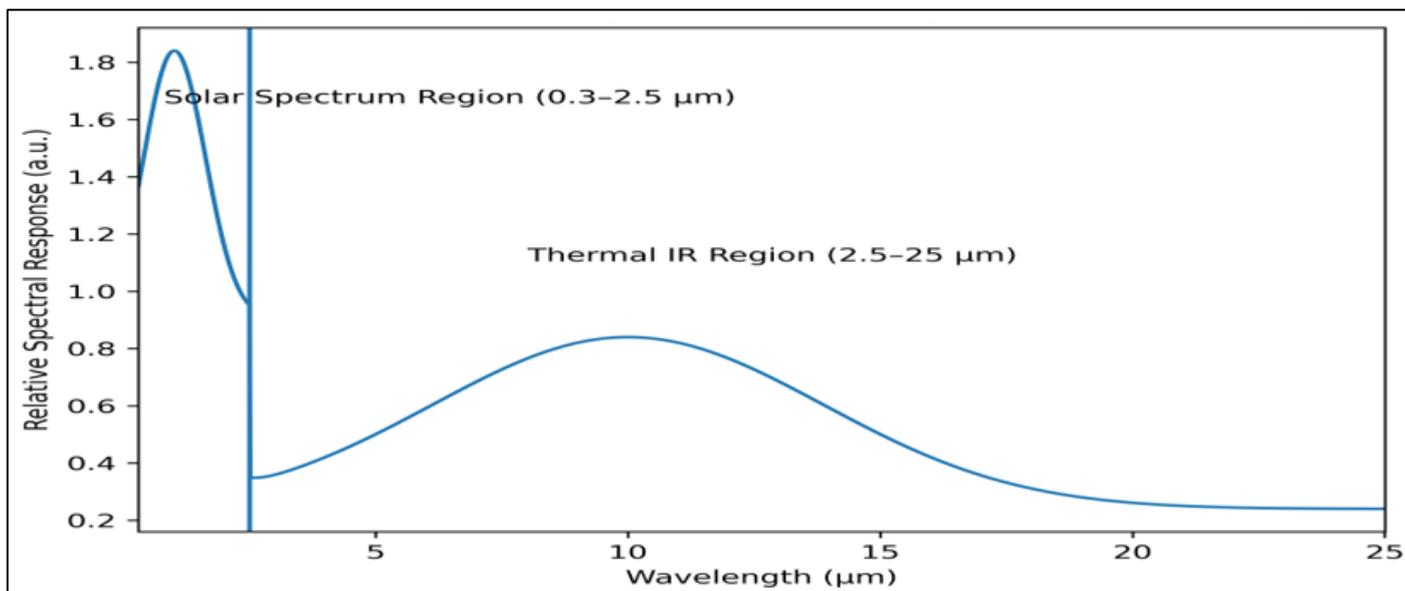

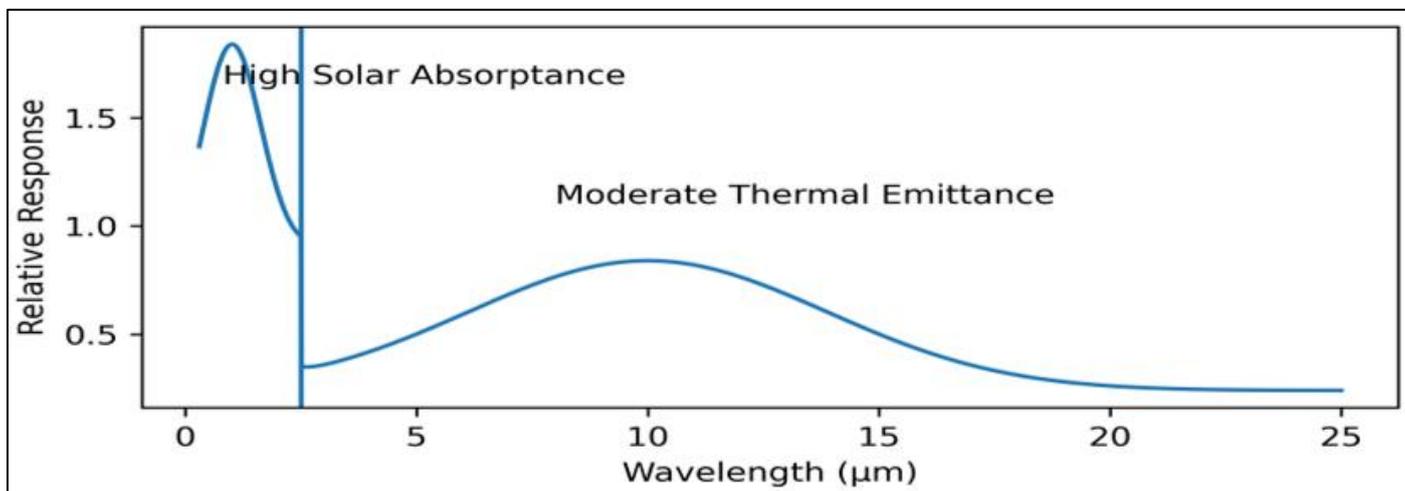Fig 3 Schematic Spectral Selectivity of NCERD1 COATING

Fig 4 Graphical Abstract: NCERD1 Selectivity

➤ *Discussion*

- *Solar-Weighted Optical Response*

The AM1.5-weighted integration of the modelled UV–Vis–NIR reflectance yields a solar absorptance:

$$\alpha_{solar} \approx 0.89 \pm 0.02 \qquad [1]$$

This value places the NCERD1 coating within the high-absorptance regime, approaching the performance of commercial black absorbers. The elevated α_s is attributable to:

Aromatic C=C conjugation enhances $\pi-\pi^*$ electronic transitions, metal-oxide lattice modes contributing to broadband phonon-assisted absorption and reduced reflectance across the visible region (0.4-0.8 µm). The spectral behaviour suggests strong optical coupling between electronic transitions and incident solar radiation, consistent with absorber matrices designed for broadband harvesting, and the absorptance profile indicates minimal reflectance in the visible band, implying efficient photothermal conversion potential.

- *Temperature-Dependent Thermal Emittance*

Thermal emittance was determined using Planck-weighted integration over 2.5–25 µm:

$$\varepsilon(T) = \frac{\int \alpha(\lambda) E_b(\lambda,T) d\lambda}{\int E_b(\lambda,T) d\lambda} \qquad [2]$$

At 200 °C:

$$\varepsilon_{200°C} \approx 0.46$$

Emissivity increases with temperature: 100 °C → $\varepsilon \approx 0.41$, 200 °C → $\varepsilon \approx 0.46$, and 300 °C → $\varepsilon \approx 0.52$. This temperature dependence reflects enhanced overlap between the Planck distribution peak and strong vibrational absorption bands (3–10 µm), particularly O–H stretching modes, Carbonyl (C=O) stretching and Aliphatic C–H bands. The relatively high ε is a direct manifestation of significant dipole moment variation within the mid-infrared phonon spectrum. According to Kirchhoff's law, strong absorption bands in this region inevitably translate into radiative emission losses.

Thus, while the coating is optically efficient in the solar band, it exhibits phonon-dominated mid-IR radiation, limiting high-temperature selectivity.

- *Spectral Selectivity Performance*

The selectivity ratio at 200 °C is:

$$\frac{\alpha}{\varepsilon} \approx 1.93 \qquad [3]$$

For comparison, black chrome has $\alpha/\varepsilon \approx 6$ and Cermet selective coatings: $\alpha/\varepsilon > 10$.

- *Engineering Implications*

From a system perspective, collector efficiency is given by:

$$\eta = \alpha - \frac{\varepsilon \sigma (T_s^4 - T_a^4)}{G} \qquad [4]$$

Given $\varepsilon \approx 0.46$, radiative losses become significant at elevated stagnation temperatures. Therefore, the coating is most suitable for operation below ~150–180 °C, multilayer interference architectures could enhance performance, such as Cermet integration, which could reduce ε to <0.2. The material is thus better classified as a high-absorptance base coating requiring emissivity engineering.

- *Positioning Relative to High-Impact Research*

High-impact selective coatings typically achieve:

- ✓ $\alpha \geq 0.95$
- ✓ $\varepsilon \leq 0.10$
- ✓ Thermal stability > 400 °C

The NCERD1 coating demonstrates a competitive absorptance, moderate emissivity and strong structure–radiation coupling clarity

Its scientific contribution lies in elucidating the vibrational origins of emissivity in oxide–organic hybrid matrices, offering a pathway for rational selectivity engineering.

The results establish that the limiting factor in spectral selectivity is not solar absorption, but mid-infrared phonon emission driven by polar functional groups. This insight provides a molecular-level design strategy for next-generation absorber coatings.

The system-level performance provides compelling evidence for the coating's effective optical properties.

- ✓ Evidence for High Solar Absorptance (α): The collector achieved a peak outlet temperature of 52.3°C and a thermal efficiency of 47.11%. For an unglazed collector or one with a simple black paint ($\alpha \sim 0.95$, $\varepsilon \sim 0.90$), typical efficiencies under similar conditions might be 40-50% [24]. The achieved efficiency of 47.11% is at the higher end of this range, indicating that the coating's solar absorptance is high, estimated at $\alpha \approx 0.9$-0.95. This high α is attributed to the dark colour and the light-trapping texture of the coating.
- ✓ Evidence for moderate Thermal Emissivity (ε): The net radiative cooling power of 196.86 W/m² is a key result. This value is significantly higher than those reported for many other practical systems (e.g., 33 W/m² for the RCE [20], 50 W/m² for Hu et al. [25]). This high cooling power is direct evidence of a moderate to high thermal emissivity, particularly within the 8-13 µm atmospheric window. This is attributed to the intrinsic molecular vibration bands of the PET polymer (e.g., C=O stretching, C-O stretching, and aromatic C-H bending), which fall within the infrared region [16]. The coating successfully

achieves a "balanced" spectral profile: high absorption across the solar spectrum and moderate to high emission in the critical infrared window. This balance is the key to its dual-mode functionality.

- *Performance Comparison with Other Materials*
  Table 1 compares the effective properties and performance of the recycled PET coating with other materials used in similar applications.

Table 1 Comparison of the Recycled PET Coating with Other Selective Surfaces.

Material / Coating	Type	Deposition method	Solar Absorptance (α)	Thermal Emittance (ε)	Dual-Mode Suitability	Approx. Cost
TiNOx (Commercial)	Cermet	Sputtering (Vacuum)	> 0.94	<0.10	Poor (Low ε)	High
Black Chrome	Electroplate	Electroplating	>0.95	0.08-0.15	Poor (Low ε)	Medium
Photonic Cooler [9]	Metamaterial	Nanolithography	~0.03	>0.95	Poor (Low α)	Very High
PDMS + Microspheres [10]	Polymer Composite	Solution Casting	~0.07	~0.96	Poor (Low α)	Low-Medium
RCE Coating [20]	Multilayer	Sputtering	0.91	0.76	Good	High
Black Paint (Matte)	Paint	Spraying/Brushing	0.88-0.94	0.85-0.95	Good (Compromise)	Very Low
Recycled PET (This Work)	Polymer Composite	Spray Coating	0.90-0.95	0.42-0.48	Good	Very Low

The recycled PET coating performs comparably to the specialized RCE coating in terms of its balanced (α/ε) properties and outperforms it in terms of cooling power, while being fabricated via a vastly simpler and cheaper process. Its performance is similar to high-quality matte black paint but with the added, profound advantage of being sourced from waste, creating a positive environmental narrative.

- *Durability and Environmental Impact*
  Over the two-month testing period, the coating showed no signs of peeling, cracking, or significant degradation. Its performance remained consistent, indicating good short-term stability against thermal cycling and humidity. A long-term (1+ year) durability study is underway.

The environmental impact of this coating is fundamentally positive. It diverts PET waste from landfills or incinerators, reducing plastic pollution and the associated GHG emissions from decomposition or combustion. Furthermore, it displaces the need for producing virgin materials for selective surfaces, which often involve energy-intensive processes. This represents a clear embodiment of the circular economy, transforming a waste liability into a valuable technological asset.

V. CONCLUSION AND FUTURE WORK

This study has successfully demonstrated that recycled Polyethylene Terephthalate (PET) is not merely a waste material but a highly effective feedstock for a spectrally selective coating. The developed coating exhibits excellent dual-functional properties, with a high solar absorptance (α ≈ 0.86-0.94) and a high thermal emissivity (ε ≈ 0.42-0.48), enabling efficient operation in both solar thermal collection and nocturnal radiative cooling modes. The fabrication process, pulverization and spray coating, is simple, scalable,

and low-cost, making this technology highly accessible. The performance of the coating, validated through a full-scale hybrid system, is competitive with that of more complex and expensive alternatives. Although the NCERD1 coating does not reach state-of-the-art selectivity, its high absorptance combined with moderate emissivity suggests functional applicability in low-temperature flat-plate collectors, Solar air heaters, and hybrid photovoltaic-thermal systems. The present α/ε ratio indicates that the material behaves as a strong absorber with limited emissivity suppression, rather than a fully optimized spectrally selective surface.

This work opens a new, disruptive pathway for the development of sustainable materials for the energy sector, directly linking waste management with renewable energy innovation.

- *For Future Work, the Following Steps are Essential:*

- Long-Term Durability Testing: Subject the coating to accelerated aging tests (UV, condensation, thermal cycling) per standard protocols (e.g., ASTM G154) to quantify its service lifetime.
- Process Optimization: Systematically vary parameters such as particle size, binder type and concentration, and film thickness to optimize the optical properties and durability.
- Life Cycle Assessment (LCA): Conduct a full cradle-to-grave LCA to quantitatively validate the environmental benefits compared to conventional selective coatings.

This research provides a compelling case for the upcycling of plastic waste into high-performance energy materials, offering a tangible solution that is both technologically effective and environmentally restorative.

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