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Absorber Plate Coatings for Enhanced Solar Still Performance: A Comprehensive Review of Mechanisms, Stability, and Economic Viability

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ABSTRACT

Solar stills are widely regarded as a suitable technology for decentralized desalination, especially in isolated and water-deficient areas, because of their simple design, low maintenance requirements, and ability to operate without external energy sources. However, their widespread implementation remains constrained by low thermal efficiency, typically ranging from 25 to 40%. Among various performance enhancement strategies, absorber plate surface engineering has emerged as one of the most practical and economical approaches; yet, previous review articles have primarily emphasized geometric modifications, phase change materials, and hybrid solar still systems, while providing only limited discussion of absorber coating technologies, their long-term durability, and techno-economic feasibility. This review critically examines absorber plate surface engineering approaches reported between 2015 and 2025 through a systematic assessment of more than 120 publications retrieved from major scientific databases using predefined inclusion and exclusion criteria. This review comparatively analyzes carbon-based nanomaterials, metal oxide nanocomposites, selective coatings, porous wick structures, and sustainable waste-derived coatings in terms of their photothermal conversion mechanisms, solar absorptivity, durability, productivity enhancement, scalability, and economic performance. Reported productivity improvements range from 15% to 65%, although direct comparison is challenging because experimental conditions, including solar intensity, basin geometry, water depth, coating preparation methods, and climatic conditions, vary considerably among studies. A durability-adjusted cost-per-liter (CPL) framework evaluates economic feasibility. The analysis indicates that nanomaterial-based coatings generally provide the highest thermal performance but are limited by high cost, adhesion issues, and insufficient long-term durability data, whereas waste-derived coatings such as biochar and waste toner powder offer a more favorable balance between efficiency, cost, and sustainability. Notably, fewer than 15% of published studies report durability testing beyond 60 days, highlighting a significant knowledge gap regarding long-term field performance under saline operating conditions. The review concludes that future research could prioritize standardized testing protocols, extended durability evaluation, scalable manufacturing methods, and environmentally sustainable coating technologies to accelerate the practical deployment of high-performance solar desalination systems.

Keywords: Solar still; Absorber plate coating; Photothermal conversion; Nanomaterials; Desalination; Durability.

1. INTRODUCTION

1.1 Background and Context

Access to clean freshwater has become a major global challenge in the 21st century. According to the World Health Organization (WHO) and the United Nations, approximately 2.2 billion people lack access to safely managed drinking water, while increasing population growth, industrialization, climate change, and groundwater depletion are expected to intensify water stress in many regions by 2050 (UNESCO, 2023; Mekonnen and Hoekstra, 2016). Conventional desalination technologies such as reverse osmosis, multi-stage flash distillation, and electrodialysis have proven effective for large-scale freshwater production, but their high energy consumption, significant capital investment, and operational complexity often make them unsuitable for remote or off-grid communities, particularly in developing regions (Elimelech and Phillip, 2011; Ghaffour *et al.* 2013). In this context, solar desalination systems, especially passive solar stills, have gained attention as a simpler, more sustainable alternative because they use freely available solar energy and can operate without external power sources (Sharon and Reddy, 2015).

The conventional basin-type solar still is valued for its simple design, ease of operation, and low maintenance requirements, but its thermal efficiency remains relatively low, generally 25–40% under normal operating conditions (Kabeel and El-Agouz, 2011; Tiwari and Sahota, 2017). This limitation has led researchers to investigate various methods for improving system performance, including stepped basin arrangements (Velmurugan and Srithar, 2011), wick-based designs (Murugavel *et al.* 2008), tubular solar still configurations (Ahsan *et al.* 2014), and the incorporation of phase change materials (Shalaby *et al.* 2016), external condensers (Kabeel *et al.* 2016), and photovoltaic-thermal hybrid systems (Kumar and Tiwari, 2010). Despite these developments, one of the most important factors influencing performance remains the absorber plate surface, which serves as the main interface for converting incoming solar radiation into the thermal energy required for evaporation.

1.2 The Absorber Plate Problem

The absorber plate serves as the primary thermal component of a solar still, converting incident solar radiation into thermal energy that drives water evaporation (Duffie and Beckman, 2013). In most conventional systems, absorber plates are fabricated from materials such as galvanized iron, aluminum, or copper and coated with commercially available matte black paint owing to its low cost and ease of application.

Conventional black paint coatings commonly used on absorber plates have several drawbacks that reduce solar still performance. Their solar absorptivity generally ranges between 0.88 and 0.92, indicating that a portion of the incoming solar radiation is lost through reflection rather than being converted into heat (Suman *et al.* 2015). In addition, these coatings usually have high thermal emissivity, which increases radiative heat loss to the surroundings, especially when the absorber surface operates at higher temperatures (Selvakumar and Barshilia, 2012). Another important concern is their limited durability under prolonged exposure to hot saline water. Studies have reported different forms of coating degradation, including peeling, blistering, chalking, and reduced adhesion, often appearing after only a few months of continuous operation (Feilizadeh *et al.* 2016; Modi *et al.* 2021).

The thermal performance of the absorber plate can be described using the overall heat-transfer coefficient between the absorber surface and the water layer in the solar still system:

$$U_{aw} = \frac{1}{\frac{1}{h_c} + \frac{t_{coat}}{k_{coat}} + R_{interface}}$$

where U_{aw} is the overall heat-transfer coefficient (W m^{-2} K^{-1}), h_c is the convective heat-transfer coefficient at the water interface (W m^{-2} K^{-1}), t_{coat} is the coating thickness (m), k_{coat} is the thermal conductivity of the coating (W m^{-1} K^{-1}), and $R_{interface}$ is the thermal contact resistance between the coating layer and the substrate material (m^2 K W^{-1}) (Incropera *et al.* 2011).

This expression is not a complete heat-transfer model for solar stills; it illustrates the fundamental role of absorber coatings in minimizing thermal resistance and improving heat-transfer efficiency. Thin coatings possessing high thermal conductivity, excellent adhesion, and high solar absorptivity facilitate greater heat transfer to the water layer, resulting in increased evaporation rates and freshwater productivity. Consequently, optimizing absorber coatings is one of the most practical and cost-effective strategies for improving solar still performance.

1.3 Review of Previous Reviews and Research Gap

Sharshir *et al.* (2017a) presented a broad review covering passive and active solar still modifications, including geometric design changes, reflector integration, and nanofluid applications, but devoted only limited discussion to absorber plate coatings. Likewise, the review by Kabeel and El-Agouz (2011) examined different productivity enhancement methods in detail, although surface coating technologies received comparatively less attention than basin design modifications. Muftah *et al.* (2014) also focused mainly on integrating phase change materials and their effect on solar still performance.

More recent studies have also examined the use of advanced materials in solar still systems. Elango *et al.* (2015) reviewed nanoparticle applications in solar stills, emphasizing nanofluids mixed with basin water rather than coatings applied to absorber surfaces. Similarly, Selvaraj and Natarajan (2018) reviewed carbon-based nanomaterials but did not include a detailed comparison with low-cost, sustainable alternative coating materials. In addition, these reviews provided limited discussion of coating durability under saline operating conditions and did not present comparative cost-per-liter evaluations for different coating types. The reviews also did not systematically examine methodological variations among experimental studies, which often lead to inconsistent or conflicting performance results.

This research gap matters because absorber plate coatings are among the most cost-effective ways to improve solar still performance. Depending on the coating material and preparation method, productivity improvements of approximately 15–65% have been reported, while material costs can range from nearly negligible for waste-derived coatings to about \$50/m² for advanced nanocomposite coatings (Arunkumar *et al.*

2018). Even at the higher end of this range, coating modification is generally less expensive than major system alterations such as geometric redesign, concentrator integration, or hybrid solar still development.

1.4 Objectives and Scope of the Review

Building on the research gaps identified above, this review aims to provide a comprehensive and critical assessment of absorber-plate coating technologies for solar still applications. The specific objectives are:

- To explain the fundamental photothermal mechanisms governing absorber coating performance, including spectral selectivity, plasmonic heating, semiconductor absorption, and porous light-trapping effects.
- To critically compare carbon-based nanomaterials, metal oxide nanocomposites, selective coatings, porous wick structures, and sustainable waste-derived coatings with respect to optical performance, thermal behavior, durability, scalability, and environmental sustainability.
- To evaluate coating durability under saline operating conditions by examining degradation mechanisms, conducting accelerated aging studies, and assessing long-term stability.
- To compare coating technologies using a unified techno-economic perspective based on durability-adjusted cost-per-liter (CPL), scalability, and practical applicability.
- To identify methodological inconsistencies across published studies and recommend standardized testing procedures for future investigations.

This review focuses on literature published between 2015 and 2025, a period when absorber coating research advanced rapidly due to advances in nanotechnology, surface engineering, and sustainable materials. Earlier studies are cited only where necessary to establish fundamental concepts or historical developments. Unlike previous reviews, this work emphasizes thermal performance, durability, economic viability, environmental impact, and industrial scalability, providing a comprehensive framework for evaluating absorber coating technologies for practical solar desalination.

2. FUNDAMENTAL MECHANISMS OF ABSORBER COATINGS

2.1 Photothermal Energy Conversion in Solar Still Absorbers

The primary function of an absorber coating in a solar still is to maximize the conversion of incident solar radiation into thermal energy while minimizing heat losses to the surroundings (Arunkumar *et al.* 2018; Atkinson *et al.* 2015; Modest, 2013; Howell *et al.* 2015). Unlike solar thermal collectors operating at 150–300°C, passive basin solar stills generally operate at 40–80°C (Kennedy, 2002). Consequently, the relative importance of optical and thermal properties differs considerably, and coating selection should be based on practical operating conditions rather than optical performance alone.

The overall freshwater productivity of a solar still depends on the amount of heat transferred from the absorber plate to the saline water. Therefore, an effective absorber coating should simultaneously exhibit:

- High solar absorptivity ($\alpha > 0.95$),
- Adequate thermal conductivity,
- Strong adhesion to the substrate,
- Resistance to saline corrosion,
- Low degradation under thermal cycling,
- Economical fabrication and scalability (Kennedy and Price, 2008; Kalogirou, 2014; Baffou and Quidant, 2013).

Many published studies emphasize improvements in solar absorptivity; however, absorptivity alone cannot explain the observed variation in productivity enhancement. Experimental investigations conducted under similar absorptivity values frequently report productivity improvements differing by more than 20%, indicating that coating adhesion, thermal conductivity, substrate properties, and environmental conditions are equally important.

Thus, absorber coating performance should be evaluated using a multi-parameter approach rather than optical properties alone.

2.2 Spectral Selectivity and Optical Characteristics

An ideal solar absorber exhibits high absorptivity in the solar wavelength region (0.28–2.5 μm) while maintaining low emissivity in the infrared region (2.5–25 μm). This property, commonly known as spectral selectivity (Link and El-Sayed, 2000; Baffou and Quidant, 2014; Neumann *et al.* 2013), improves photothermal conversion efficiency by maximizing absorbed solar energy while reducing radiative heat loss.

According to Kirchhoff's law, spectral absorptivity equals spectral emissivity under thermal equilibrium (Bonaccorso *et al.* 2010). However, solar absorbers operate under non-equilibrium conditions because incoming short-wave solar radiation and outgoing long-wave thermal radiation occupy different wavelength ranges. This wavelength separation enables engineering of coatings with high solar absorption and relatively low infrared emission.

Although highly selective coatings significantly improve performance in evacuated tube collectors and concentrated solar power systems (Nair *et al.* 2008; Loh *et al.* 2010), their advantage is comparatively smaller for passive solar stills because radiative losses represent only a fraction of the total heat loss (Luo *et al.* 2011). Convective heat transfer, evaporation, and basin-water interactions dominate overall system performance.

Consequently, increasing absorptivity from 0.90 to 0.97 generally produces more practical benefits than reducing emissivity from 0.15 to 0.05.

This distinction explains why relatively inexpensive carbon-based coatings often provide productivity improvements comparable to expensive commercial selective coatings.

2.3 Comparison of Photothermal Conversion Mechanisms

Different absorber coatings convert solar radiation into heat through different physical mechanisms, as shown in Fig. 1. Understanding these mechanisms helps explain why coatings with similar absorptivity may perform differently under identical operating conditions.

2.3.1 Carbon-based Nanomaterials

Graphene, reduced graphene oxide (rGO), and carbon nanotubes absorb photons through π-electron transitions within extended conjugated carbon networks (Cao *et al.* 2014; Cao *et al.* 2015; Drelich *et al.* 2011).

Advantages include:

- Broadband absorption,
- Excellent thermal conductivity,
- Rapid heat generation,
- Chemical stability.

However, practical implementation is limited by:

- High material cost,
- Dispersion difficulties,
- Poor adhesion,
- Nanoparticle agglomeration,
- Scale-up challenges.

Experimental studies report productivity enhancement ranging from 30–65% (Quéré, 2008; Kim *et al.* 2012; Fujishima *et al.* 2008), although much of this variation arises from coating preparation methods rather than intrinsic material properties (Hashimoto *et al.* 2005; Balandin *et al.* 2008).

2.3.2 Plasmonic Nanoparticles

Metallic nanoparticles such as gold, silver, and copper nanoparticles generate heat through localized surface plasmon resonance (LSPR) (Novoselov *et al.* 2012; Shanmugan *et al.* 2012; Kabeel *et al.* 2014a).

When incident light excites free electrons within metallic nanoparticles, rapid electron-phonon interactions convert optical energy into heat.

Although plasmonic coatings demonstrate excellent laboratory performance, their practical application in solar stills remains limited because:

- Noble metals are expensive,
- Resonance occurs over relatively narrow wavelength bands,
- Large-scale fabrication remains difficult,
- Long-term corrosion resistance under saline conditions has not been adequately demonstrated (Sahota and Tiwari, 2016; Sun *et al.* 2011).

Consequently, plasmonic coatings currently remain more attractive for laboratory research than commercial solar desalination systems.

2.3.3 Semiconductor Metal Oxides

Semiconductor coatings such as CuO, Fe_3O_4, ZnO and TiO_2 absorb solar radiation through band-gap electronic transitions (Prasher, 2010; Wang *et al.* 2008; Kim *et al.* 2011; Mizuno *et al.* 2009).

Compared with carbon nanomaterials, semiconductor coatings generally:

- Possess superior chemical stability,
- Are less expensive,
- Exhibit better corrosion resistance, but their optical response depends strongly on band-gap energy.

CuO exhibits relatively high visible absorption and has therefore become one of the most investigated metal oxides for solar still applications (Elango *et al.* 2015; Sharshir *et al.* 2017b).

In contrast, TiO_2 absorbs primarily ultraviolet radiation and contributes mainly through photocatalytic self-cleaning rather than direct photothermal enhancement (Shahrul *et al.* 2014; Ma *et al.* 2010).

2.3.4 Porous Light-trapping Structures

Porous coatings enhance solar absorption through repeated internal reflection within surface cavities (Liu *et al.* 2015).

Rather than relying solely on intrinsic optical absorption, porous materials increase photon residence time by multiple scattering, thereby increasing the probability of absorption.

In addition, porous absorbers frequently function as wick materials that:

- Transport saline water,
- Enlarge evaporation area,
- Localize heating near the water-air interface.

This mechanism has recently become one of the most promising strategies for interfacial solar evaporation (Bixler and Bhushan, 2012; Selvakumar and Barshilia, 2012).

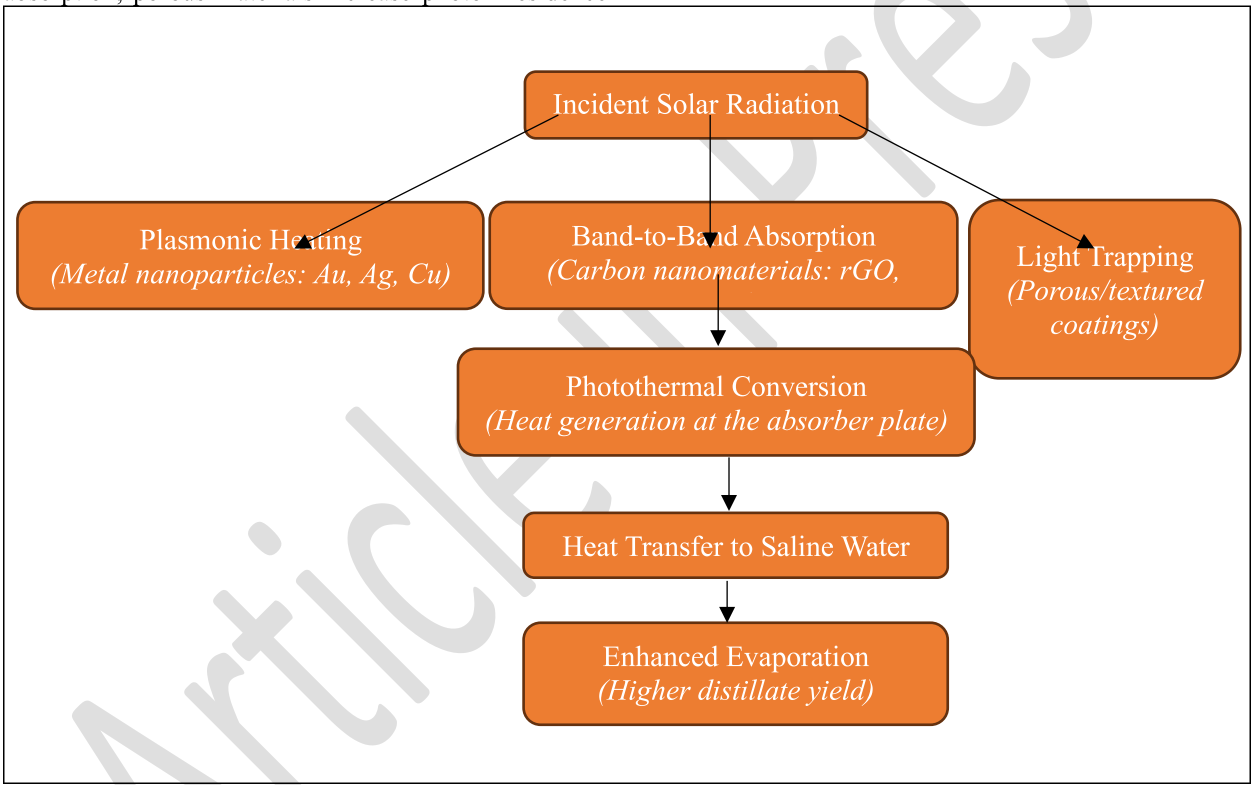

Fig. 1: Photothermal mechanism

2.4 Critical Comparison of Photothermal Mechanisms

Although numerous coating materials have been proposed, no single photothermal mechanism simultaneously satisfies all performance requirements.

Carbon nanomaterials generally provide the highest thermal efficiency but suffer from poor adhesion and relatively high cost.

Metal oxide coatings offer superior durability but often yield smaller productivity gains because of lower broadband absorption.

Selective coatings provide excellent optical characteristics but require expensive deposition techniques.

Porous absorbers improve evaporation area and reduce bulk-water heating; however, biofouling and long-term structural degradation remain major concerns.

Therefore, coating selection should consider not only optical efficiency but also durability, economic feasibility, manufacturing complexity, environmental safety, and long-term field performance (Kabeel *et al.* 2016; Bakthavatchalam *et al.* 2020; Zoolfakar *et al.* 2014).

2.5 Wettability, Fouling and Durability

Surface wettability strongly influences evaporation, salt crystallization, and long-term absorber performance.

Hydrophilic coatings promote thin water films that enhance heat transfer and suppress localized salt accumulation (Sathyamurthy *et al.* 2014; Elango and Kalidasa, 2015).

Several investigations report lower scale adhesion on hydrophilic surfaces because continuous water films reduce local supersaturation.

Conversely, some researchers suggest that hydrophobic coatings facilitate dropwise evaporation and reduce mineral attachment (Omara *et al.* 2015).

These apparently conflicting findings arise because the dominant mechanism depends upon operating conditions, water chemistry, and surface morphology (Sharshir *et al.* 2016; Chen and Mao, 2007; Kabeel *et al.* 2014; Nguyen *et al.* 2013).

Consequently, neither hydrophilic nor hydrophobic behavior should be considered universally superior.

Instead, optimizing surface wettability for intended operating conditions is a more practical design strategy.

Future investigations should also consider:

- Fouling resistance,
- UV stability,
- Thermal cycling,
- Coating delamination,
- Corrosion resistance,

since these factors largely determine long-term freshwater production.

Table 1. Comparative assessment of fundamental photothermal mechanisms

Mechanism	Typical materials	Absorptivity	Advantages	Limitations	Suitability
Band-to-band absorption	Graphene, CNT, rGO	0.95–0.98	Highest efficiency	Expensive, adhesion issues	High
Localized surface plasmon resonance	Au, Ag, Cu	0.94–0.98	Extremely rapid heating	Very high cost	Moderate
Semiconductor absorption	CuO, TiO_2, Fe_3O_4	0.91–0.96	Stable, economical	Lower optical response	High
Light trapping	Biochar, porous ceramics, foams	0.92–0.97	Low cost, large evaporation area	Biofouling, structural degradation	Very high

2.6 Critical Summary

The literature shows that improving solar absorptivity alone is insufficient to develop commercially viable absorber coatings. While nanomaterial-based coatings achieve the highest short-term productivity enhancement, their practical application is constrained by high cost, limited durability, adhesion challenges, and manufacturing complexity. In contrast, porous carbon materials, biochar, and waste-derived coatings offer a better balance of optical performance, durability, scalability, and economic feasibility. Therefore, future research should prioritize multifunctional coatings that integrate efficient photothermal conversion with strong substrate adhesion, resistance to saline fouling, environmental safety, and long-term operational stability under realistic solar still conditions.

3. CLASSIFICATION AND CRITICAL ANALYSIS OF ABSORBER COATINGS

3.1 Carbon-based Nanomaterials

Carbon-based materials have emerged as one of the most extensively investigated absorber coating categories for enhancing the thermal performance of passive solar stills. Their popularity arises from the unique combination of high solar absorptivity, broadband optical absorption, excellent thermal conductivity, chemical stability, and relatively low density. Depending on their structure and degree of graphitization, carbon-based coatings include graphene and reduced graphene oxide (rGO), carbon nanotubes (CNTs), carbon black, candle soot, activated carbon, biochar, and porous carbon foams (Shanmugan *et al.* 2012; Kabeel *et al.* 2014; Sahota and Tiwari, 2016; Sun *et al.* 2011; Prasher, 2010; Wang *et al.* 2008; Kim *et al.* 2011; Mizuno *et al.* 2009;

Elango *et al.* 2015; Sharshir *et al.* 2017a; Shahrul *et al.* 2014; Ma *et al.* 2010; Liu *et al.* 2015; Bixler and Bhushan, 2012; Selvakumar and Barshilia, 2012; Kabeel *et al.* 2016; Zhu *et al.* 2018; Murugavel *et al.* 2010; Ahmad *et al.* 2014; Manokar *et al.* 2018). Although these materials share similar optical characteristics, their practical performance varies considerably because of differences in morphology, coating preparation methods, substrate compatibility, binder selection, and operating conditions rather than intrinsic material properties alone (Shanmugan *et al.* 2012; Kabeel *et al.* 2014a; Elango *et al.* 2015; Sharshir *et al.* 2017b; Kabeel *et al.* 2016).

3.1.1 Graphene and Reduced Graphene Oxide (rGO)

Graphene and reduced graphene oxide (rGO) have attracted considerable attention because of their exceptional photothermal conversion capability. Their two-dimensional sp^2-bonded carbon network provides broadband solar absorption and high in-plane thermal conductivity, enabling efficient conversion of incident solar radiation into heat (Shanmugan *et al.* 2012; Kabeel *et al.* 2014a). Experimental investigations have reported freshwater productivity improvements ranging from approximately 30–45% compared with conventional black-painted absorbers (Shanmugan *et al.* 2012; Kabeel *et al.* 2014a).

However, these reported improvements should be interpreted cautiously because experimental conditions differ substantially among investigations. Variations in solar irradiance (approximately 780–920 W m^{-2}), absorber material (copper or aluminum), coating thickness, binder chemistry, basin geometry, feedwater depth, and climatic conditions all influence thermal performance (Shanmugan *et al.* 2012; Kabeel *et al.* 2014a). Consequently, differences in reported productivity cannot be attributed solely to graphene itself but instead reflect the combined influence of coating formulation and experimental methodology.

Despite their excellent optical properties, graphene-based coatings continue to face important practical challenges. Uniform dispersion within polymer matrices remains difficult because graphene sheets tend to agglomerate through strong van der Waals interactions, while weak adhesion to metallic substrates frequently results in coating delamination during prolonged saline exposure and repeated thermal cycling (Shanmugan *et al.* 2012; Kim *et al.* 2011). Kim *et al.* (2011) demonstrated that polydopamine-functionalized rGO coatings retained approximately 91% of their initial absorptivity after 60 days of saline immersion, indicating improved durability; however, long-term field validation under realistic outdoor conditions remains unavailable.

From an economic perspective, graphene coatings remain significantly more expensive than conventional carbon coatings because of high material cost and relatively complex fabrication processes. Therefore, although graphene offers excellent short-term thermal performance, further developments in scalable manufacturing, coating durability, and cost reduction are necessary before widespread commercialization can be achieved (Shanmugan *et al.* 2012; Kim *et al.* 2011).

3.1.2 Carbon Nanotubes (CNTs) Coating

Multi-walled carbon nanotubes (MWCNTs) possess excellent optical absorption, high thermal conductivity, and interconnected conductive pathways that facilitate rapid heat transfer within the coating layer (Elango *et al.* 2015; Sharshir *et al.* 2017b). Consequently, CNT-based coatings have consistently produced some of the highest productivity enhancements reported for passive solar stills.

Nevertheless, the literature reveals substantial variation in reported performance. Elango *et al.* (2015) reported productivity enhancement of approximately 65.4%, whereas Sharshir *et al.* (2017b) observed an increase of approximately 38%, despite employing similar CNT concentrations. Such differences are unlikely to arise solely from nanotube properties. Instead, they are more reasonably attributed to variations in substrate thermal conductivity, binder selection, coating thickness, dispersion quality, operating temperature, and solar intensity (Elango *et al.* 2015; Sharshir *et al.* 2017b).

Another important limitation concerns reproducibility. Laboratory-scale investigations generally achieve homogeneous CNT dispersion through ultrasonication, but this process becomes increasingly difficult and energy-intensive at industrial scale. Poor dispersion promotes nanotube agglomeration, reducing effective solar absorption and increasing thermal resistance within the coating layer (Elango *et al.* 2015; Sharshir *et al.* 2017a).

Long-term durability also remains insufficiently investigated. Most published studies evaluate coating performance for periods shorter than three months, providing limited evidence regarding service life under continuous saline operating conditions. Consequently, additional long-term outdoor testing is required before CNT coatings can be recommended for commercial solar desalination systems (Sharshir *et al.* 2017b).

3.1.3 Carbon Black and Soot-based Coatings

Carbon black, candle soot, and combustion-derived carbon coatings are simple, economical alternatives to engineered nanomaterials. Their highly disordered carbon structure provides broadband optical absorption across the visible and near-infrared spectrum, resulting in appreciable photothermal conversion efficiency (Kabeel *et al.* 2016).

Compared with graphene and CNT coatings, carbon black typically produces more moderate productivity improvements of approximately 20–30% (Kabeel *et al.* 2016). Nevertheless, their extremely low material cost and straightforward preparation make them attractive for decentralized freshwater production in resource-limited regions.

A major disadvantage of soot-based coatings is poor mechanical durability. Since many soot coatings are deposited without protective binders, they frequently suffer from weak adhesion, mechanical abrasion, salt crystallization damage, and gradual loss of absorptivity during repeated wetting and drying cycles (Kabeel *et al.* 2016; Chen *et al.* 2017). Therefore, although soot coatings exhibit favorable initial optical performance, their long-term stability remains inferior to engineered nanocomposite coatings.

Furthermore, preparing soot coatings through uncontrolled combustion may generate particulate emissions, underscoring the need for environmentally responsible fabrication procedures.

3.1.4 Activated Carbon and Biochar-based Coatings

Growing interest in sustainable materials has stimulated research on activated carbon and biochar as environmentally friendly absorber coatings. Activated carbon possesses a highly porous structure with specific surface areas approaching 800–2000 $m^2\ g^{-1}$, promoting both efficient solar absorption and enhanced heat localization (Ahmad *et al.* 2014; Manokar *et al.* 2018). Similarly, biochar derived from agricultural residues, including rice husk, coconut shell, and sugarcane bagasse, converts biomass waste into valuable photothermal materials (Manokar *et al.* 2018).

Experimental investigations have shown that biochar-based coatings can improve productivity by about 35–38%, approaching levels reported for several nanomaterial coatings while requiring only a fraction of the material cost (Manokar *et al.* 2018). Their porous morphology promotes multiple internal reflections, increases photon residence time, and improves heat transfer between the absorber and saline water (Ahmad *et al.* 2014; Manokar *et al.* 2018).

Despite these advantages, coating performance depends strongly on biomass source, carbonization temperature, activation process, ash content, and particle size distribution, resulting in considerable variability among published studies (Ahmad *et al.* 2014; Manokar *et al.* 2018). Standardized preparation methods are therefore required to enable reliable comparison and facilitate industrial implementation.

3.1.5 Critical Assessment of Carbon-based Coatings

Collectively, carbon-based coatings are among the most promising absorber categories because they combine excellent optical absorption with relatively simple fabrication methods. However, comparison of published investigations demonstrates that coating material alone does not determine solar still performance. Productivity improvements are strongly influenced by solar irradiance, substrate properties, coating thickness, binder formulation, water depth, and climatic conditions (Shanmugan *et al.* 2012; Kabeel *et al.* 2014a; Elango *et al.* 2015; Sharshir *et al.* 2017b; Manokar *et al.* 2018). Consequently, direct comparison of reported productivity enhancements should be undertaken cautiously.

Among carbon-based materials, graphene and CNT coatings generally deliver the highest short-term thermal performance but remain constrained by high material cost, dispersion challenges, adhesion limitations, and insufficient long-term durability data (Shanmugan *et al.* 2012; Kim *et al.* 2011; Elango *et al.* 2015; Sharshir *et al.* 2017b). Carbon black and soot coatings are economically attractive but exhibit inferior mechanical stability (Kabeel *et al.* 2016). In contrast, biochar and activated carbon provide a more balanced combination of efficiency, sustainability, cost-effectiveness, and scalability, making them particularly promising for practical solar desalination systems (Ahmad *et al.* 2014; Manokar *et al.* 2018).

Future research could therefore focus on developing durable, low-cost, and environmentally sustainable carbon-based coatings while adopting standardized testing protocols and long-term field validation to establish their practical viability under realistic saline operating conditions (Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995; Carlsson *et al.* 2000; Sampathkumar *et al.* 2010).

3.2 Metal Oxide-based Absorber Coatings

Metal oxide nanomaterials are among the most widely investigated absorber coatings for passive solar still applications because they combine good optical properties with relatively low cost, chemical stability, and ease of fabrication. Unlike carbon-based nanomaterials, whose performance is largely governed by delocalized electron transport, metal oxides convert incident solar radiation into thermal energy primarily through semiconductor band-gap transitions and lattice vibrations. Their optical response depends strongly on band-gap energy, particle morphology, crystal structure, and coating architecture, resulting in considerable variation in reported solar still performance (Sathyamurthy *et al.* 2014; Elango and Kalidasa, 2015; Omara *et al.* 2015; Sharshir *et al.* 2016; Chen and Mao, 2007; Kabeel *et al.* 2014; Nguyen *et al.* 2013; Rashidi *et al.* 2017; Kabeel *et al.* 2019; Atkinson *et al.* 2015; McDonald, 1975).

Although numerous metal oxides have been investigated, copper oxide (CuO), titanium dioxide (TiO_2), iron oxide (Fe_3O_4), zinc oxide (ZnO), and hybrid nanocomposites have received the most attention because they offer an effective balance of thermal performance, durability, and manufacturing cost.

3.2.1 Copper Oxide (CuO) Coatings

Copper oxide is among the most extensively studied semiconductor coatings for solar desalination because of its narrow band gap (approximately 1.2–1.9 eV), which enables efficient absorption of visible solar radiation (Sathyamurthy *et al.* 2014; Elango and Kalidasa, 2015). In addition, CuO nanoparticles exhibit relatively high thermal conductivity, good corrosion resistance, and compatibility with conventional coating techniques such as spray coating, dip coating, and paint-based formulations.

Reported productivity improvements for CuO-coated absorber plates generally range from 25% to 40% under different operating conditions (Sathyamurthy *et al.* 2014; Elango and Kalidasa, 2015). However, direct comparison between studies remains difficult because experimental conditions differ considerably. Factors such as solar irradiance (approximately 780–900 W m^{-2}), absorber material, nanoparticle loading, coating thickness, binder composition, and water depth significantly influence thermal performance. Consequently, the superior performance reported in some investigations should not be interpreted as an intrinsic property of CuO alone but rather as the combined effect of material selection and experimental design.

Compared with graphene and CNT coatings, CuO generally produces slightly lower peak productivity enhancement but offers important practical advantages, including lower material cost, improved chemical stability, and simpler large-scale manufacturing. These characteristics make CuO one of the most attractive semiconductor coatings for practical solar still applications.

3.2.2 Titanium Dioxide (TiO_2) Coatings

Researchers have extensively investigated titanium dioxide because of its exceptional chemical stability, resistance to ultraviolet degradation, and photocatalytic self-cleaning capability (Kabeel *et al.* 2014b; Banerjee *et al.* 2015). Unlike CuO, TiO_2 possesses a relatively wide band gap (approximately 3.2 eV), limiting direct absorption primarily to ultraviolet radiation, which constitutes only a small fraction of the solar spectrum.

Consequently, TiO_2 coatings generally produce more modest productivity improvements, typically around 15–20% under comparable operating conditions (Kabeel *et al.* 2014b). Their principal advantage lies not in maximizing photothermal conversion but in reducing organic fouling and improving long-term surface cleanliness through photocatalytic degradation of contaminants.

Recent investigations have demonstrated that combining TiO_2 with carbon-based materials such as reduced graphene oxide substantially improves visible-light absorption while preserving photocatalytic activity (Nguyen *et al.* 2013). Such hybrid nanocomposites have achieved productivity improvements exceeding 40%, illustrating the benefits of integrating complementary photothermal mechanisms.

Despite these promising developments, large-scale implementation remains constrained by fabrication complexity and the additional processing steps required to produce stable composite coatings.

3.2.3 Iron Oxide (Fe_3O_4) and Other Metal Oxides

Iron oxide nanoparticles (Fe_3O_4) have attracted increasing interest because they combine moderate photothermal performance with low toxicity, chemical stability, and relatively low production cost (Kabeel *et al.* 2019). Reported productivity improvements of approximately 30–35% suggest that Fe_3O_4 coatings can provide thermal performance comparable to several other semiconductor materials while maintaining good corrosion resistance under saline operating conditions.

Zinc oxide (ZnO), manganese oxide (MnO_2), nickel oxide (NiO), and cobalt oxide have also been investigated; however, comparatively fewer studies have evaluated their application in passive solar stills (Atkinson *et al.* 2015; McDonald, 1975). Most available investigations remain limited to laboratory-scale experiments, making it difficult to assess their long-term suitability for practical desalination systems.

The relatively small number of comparative studies involving multiple metal oxides under identical operating conditions represents an important research gap. Without standardized experimental protocols, identifying the optimum semiconductor coating remains challenging.

3.2.4 Hybrid Metal Oxide Nanocomposites

Recent research has shifted toward hybrid nanocomposite coatings that combine semiconductor nanoparticles with highly conductive carbon materials. Examples include TiO_2-rGO, CuO-graphene, Fe_3O_4-CNT, and CuO-carbon black composites (Nguyen *et al.* 2013; Rashidi *et al.* 2017; Kabeel *et al.* 2019).

The principal advantage of hybrid coatings is the synergistic interaction between their components. Carbon materials provide broadband solar absorption and rapid heat transfer, whereas semiconductor nanoparticles improve mechanical stability, corrosion resistance, and photocatalytic properties. This combination often yields better thermal performance than either constituent alone.

Nevertheless, the degree of improvement depends strongly on nanoparticle dispersion, interfacial bonding, composite composition, and fabrication method. Excessive nanoparticle loading may increase optical scattering and reduce coating uniformity, while inadequate dispersion promotes agglomeration that decreases thermal conductivity. Consequently, optimization of composite composition remains an active area of research.

Economic considerations also become increasingly important as coating complexity increases. Although hybrid nanocomposites often outperform single-component coatings, their higher manufacturing cost and more complex preparation procedures may offset some of their thermal advantage, particularly for low-cost rural desalination systems.

3.2.5 Durability and Practical Considerations

Compared with carbon nanomaterials, semiconductor metal oxides generally exhibit superior resistance to oxidation, ultraviolet radiation, and chemical degradation. Nevertheless, coating failure remains possible because of repeated thermal cycling, differential thermal expansion between coating and substrate, and salt crystallization during prolonged saline exposure (Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995; Al-Karaghouli and Kazmerski, 2013).

Most published investigations evaluate thermal performance for periods shorter than 60–90 days, providing insufficient information regarding long-term service life under realistic outdoor operating conditions. Furthermore, laboratory durability tests are commonly performed using controlled saline solutions that do not fully reproduce the complex chemistry of natural seawater or brackish groundwater. Consequently, extrapolating laboratory observations to practical field performance should be undertaken with caution.

Environmental considerations should also be recognized. Although metal oxide nanoparticles are generally less hazardous than carbon nanotubes, nanoparticle release caused by coating degradation remains a potential environmental concern. Future coating formulations should therefore emphasize strong substrate adhesion and environmentally benign binder systems to minimize nanoparticle leaching during operation and disposal (Hischier and Walser, 2012; Poland *et al.* 2008).

3.2.6 Critical Assessment of Metal Oxide Coatings

Metal oxide coatings represent an attractive compromise between performance, durability, and economic feasibility. While they generally do not achieve the exceptionally high productivity improvements reported for graphene or carbon nanotube coatings, they offer superior chemical stability, lower manufacturing cost, and greater potential for large-scale implementation. Among the materials investigated, CuO appears to offer the most favorable balance between optical performance and practical applicability, whereas TiO_2-based coatings are particularly valuable when long-term fouling resistance is prioritized.

Nevertheless, the literature remains dominated by short-term laboratory investigations employing different operating conditions, coating preparation methods, and performance metrics. These methodological inconsistencies limit meaningful comparison between reported studies and hinder identification of the most suitable coating technology for commercial deployment.

Future research could therefore focus on standardized experimental protocols, long-term outdoor durability evaluation, environmentally sustainable fabrication methods, and comprehensive techno-economic assessment. Comparative investigations evaluating multiple semiconductor coatings under identical operating conditions would provide a more reliable basis for selecting absorber materials for practical solar desalination systems (Sathyamurthy *et al.* 2014; Elango and Kalidasa, 2015; Omara *et al.* 2015; Sharshir *et al.* 2016; Chen and Mao, 2007; Kabeel *et al.* 2014; Nguyen *et al.* 2013; Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995; Carlsson *et al.* 2000; Sampathkumar *et al.* 2010; Rashidi *et al.* 2017; Kabeel *et al.* 2019; Atkinson *et al.* 2015; McDonald, 1975; Banerjee *et al.* 2015; Al-Karaghouli and Kazmerski, 2013; Hischier and Walser, 2012; Poland *et al.* 2008; Hasson *et al.* 1968; Wang *et al.* 2014; Betz *et al.* 2010; Plueddemann, 1991; Lee *et al.* 2007; Roes *et al.* 2007).

3.3 Selective Solar Absorber Coatings

Selective solar absorber coatings have been widely employed in solar thermal collectors because they maximize solar energy absorption while minimizing infrared radiative heat losses. Unlike conventional black coatings, which generally exhibit both high absorptivity and high emissivity, selective coatings are designed to provide high solar absorptivity ($\alpha > 0.95$) together with low thermal emissivity ($\varepsilon < 0.15$), thereby improving the net thermal energy retained by the absorber surface (Kumar and Tiwari, 2009; Cao *et al.* 2014; Zhang *et al.* 1996; Barshilia *et al.* 2011). Although this concept has been successfully commercialized for medium- and high-temperature solar thermal applications, its effectiveness in passive basin solar stills remains under investigation because solar stills operate at substantially lower temperatures than conventional solar collectors.

The available literature indicates that selective coatings can improve freshwater productivity by reducing radiative heat losses from the absorber plate; however, the magnitude of improvement depends strongly on climatic conditions, absorber temperature, basin configuration, and coating durability. Consequently, their practical advantages should be evaluated within the specific thermal operating range of passive solar stills rather than being directly extrapolated from solar collector applications.

3.3.1 Spectrally Selective Coatings

The performance of selective coatings is governed by spectral selectivity, whereby the coating absorbs short-wavelength solar radiation efficiently while suppressing long-wave infrared emission. This behavior is generally achieved using multilayer structures composed of metallic substrates, infrared-reflective interlayers, and spectrally absorbing ceramic or cermet top coatings (Kumar and Tiwari, 2009).

Experimental studies have reported productivity improvements ranging from 20% to 40% for solar stills incorporating selective absorber coatings (Kumar and Tiwari, 2009; Cao *et al.* 2014; Zhang *et al.* 1996). Nevertheless, comparison among published investigations remains difficult because absorber temperatures rarely exceed 80°C in passive solar stills. At these relatively low temperatures, evaporative and convective heat losses often dominate the energy balance, reducing the relative benefit of lowering radiative emissivity.

This observation suggests that improvements reported for selective coatings should not be interpreted solely as a consequence of spectral selectivity. Instead, coating morphology, thermal conductivity, adhesion, and surface roughness also contribute significantly to overall performance. Therefore, future investigations should quantify the individual contribution of optical selectivity relative to other heat-transfer mechanisms.

3.3.2 Cermet-based Selective Coatings

Cermet (ceramic-metal composite) coatings are among the most successful classes of commercial selective absorbers because they combine excellent optical performance with relatively high thermal stability (Cao *et al.* 2014; Zhang *et al.* 1996; Barshilia *et al.* 2011). Typical cermet coatings consist of metallic nanoparticles embedded in dielectric ceramic matrices, allowing precise control of solar absorptivity and infrared emissivity by optimizing particle size, composition, and volume fraction.

Compared with conventional black paints, cermet coatings generally offer higher thermal efficiency and improved oxidation resistance. However, their fabrication frequently requires sophisticated deposition techniques such as magnetron sputtering, vacuum evaporation, or chemical vapor deposition. These manufacturing processes increase production cost and require specialized equipment that may not be economically justified for low-cost solar desalination systems.

Furthermore, only a limited number of studies have investigated cermet coatings directly in passive solar stills. Most available information originates from solar water heating or concentrating solar collector applications operating under substantially different thermal conditions. Consequently, additional experimental validation under realistic solar still operating environments is required before their practical superiority can be confirmed.

3.3.3 Black Chrome, Black Nickel and Black Cobalt Coatings

Electrochemically deposited black chrome, black nickel, and black cobalt coatings have historically been among the most widely used commercial selective absorber surfaces because of their excellent optical characteristics and good corrosion resistance (Chen *et al.* 2017; Minasian and Al-Karaghouli, 1995; Sakthivel *et al.* 2010; Velmurugan *et al.* 2008a). These coatings generally exhibit absorptivity values exceeding 0.94 while maintaining relatively low infrared emissivity.

Black chrome has demonstrated particularly good long-term thermal stability under outdoor exposure; however, chromium electroplating involves toxic hexavalent chromium compounds that present significant environmental and occupational health concerns. Increasingly stringent environmental regulations have therefore reduced industrial interest in chromium-based coatings despite their favorable optical performance.

Black nickel coatings provide a lower-cost alternative with acceptable optical properties, although their durability under prolonged saline exposure remains less extensively documented. Similarly, black cobalt coatings exhibit promising optical characteristics but have received comparatively little attention in solar still applications because of limited commercial availability and relatively high material costs.

These observations demonstrate that environmental compliance and manufacturing sustainability have become increasingly important criteria for coating selection alongside optical performance.

3.3.4 Vacuum-deposited and Advanced Thin-film Coatings

Advances in thin-film deposition technologies have enabled the development of highly engineered absorber coatings incorporating transition metal nitrides, carbides, oxides, and multilayer nanostructures (Zhu *et al.* 2018; Xu *et al.* 2017; Ghasemi *et al.* 2014). Magnetron sputtering and atomic layer deposition allow precise control of coating thickness and composition, resulting in excellent optical performance and superior thermal stability.

Although these coatings demonstrate impressive laboratory performance, their application in passive solar stills remains limited for several reasons. First, sophisticated vacuum deposition equipment substantially increases manufacturing cost. Second, coating large absorber plates uniformly becomes increasingly challenging as surface area increases. Third, damage occurring during field operation generally requires complete replacement rather than simple repainting, increasing maintenance costs over the system lifetime.

Consequently, while advanced thin-film coatings may suit specialized high-performance desalination systems, their widespread use in decentralized rural water purification remains economically challenging.

3.3.5 Durability, Scalability and Economic Considerations

One of the principal advantages of selective coatings is their excellent thermal stability. Commercial selective coatings have demonstrated long operational lifetimes in solar thermal collectors, often exceeding 15–20 years under appropriate operating conditions (Cao *et al.* 2014; Zhang *et al.* 1996; Barshilia *et al.* 2011). However, similar long-term durability data are largely unavailable for passive solar still applications, where continuous contact with saline water introduces additional degradation mechanisms including salt crystallization, chloride-induced corrosion, coating delamination, and mineral scaling.

Economic considerations also influence coating selection. Although selective coatings improve thermal efficiency, their higher manufacturing costs frequently outweigh the relatively modest productivity gains achieved under low-temperature solar still operating conditions. Consequently, the cost per liter of freshwater produced may not decrease proportionally with increasing thermal efficiency.

Several comparative analyses indicate that inexpensive carbon-based coatings or waste-derived photothermal materials often provide more favorable economic performance despite slightly lower optical efficiency (Wang *et al.* 2016). Therefore, cost-effectiveness should be evaluated using durability-adjusted performance metrics rather than absorptivity alone.

3.3.6 Critical Assessment of Selective Coatings

Selective solar absorber coatings remain among the most optically efficient surface treatments currently available. Nevertheless, the literature indicates that their advantages become less pronounced under the relatively low operating temperatures characteristic of passive solar stills. Because evaporation and convection dominate the overall energy balance, improvements obtained through reduced infrared emissivity are smaller than those achieved in conventional solar thermal collectors.

Compared with carbon-based and semiconductor coatings, selective coatings provide superior optical performance and excellent long-term stability but require more complex fabrication methods and substantially higher manufacturing costs. These limitations reduce their attractiveness for low-cost decentralized desalination systems where economic feasibility is a primary consideration.

Future research could therefore prioritize developing low-cost selective coatings that can be fabricated using scalable deposition techniques while maintaining adequate durability under saline operating conditions. Comparative studies evaluating selective coatings alongside carbon-based and metal oxide coatings under identical experimental conditions are particularly needed to establish their true practical value for solar desalination applications (Zhu *et al.* 2018; Kumar and Tiwari, 2009; Cao *et al.* 2014; Zhang *et al.* 1996; Barshilia *et al.* 2011; Chen *et al.* 2017; Minasian and Al-Karaghouli, 1995; Sakthivel *et al.* 2010; Velmurugan *et al.* 2008; Xu *et al.* 2017; Xu *et al.* 2017; Ghasemi *et al.* 2014; Wang *et al.* 2016).

3.4 Porous, Wick-assisted and Interfacial Photothermal Absorber Coatings

Recent advances in solar desalination have shifted attention from conventional absorber plate heating toward localized interfacial evaporation, where heat generation is concentrated near the water–air interface rather than throughout the entire water volume. Porous and wick-assisted absorber coatings have emerged as promising alternatives because they combine efficient solar absorption with continuous water transport, reduced thermal losses, and enhanced evaporation kinetics (Murugavel *et al.* 2010; Lehmann and Joseph, 2015). Unlike dense metallic coatings, these materials utilize interconnected pore networks that simultaneously trap incident solar radiation, supply water through capillary action, and confine thermal energy to the evaporation zone.

The increasing interest in porous absorber systems reflects a transition from maximizing absorber temperature alone to optimizing overall heat utilization. Consequently, coating performance should be assessed by considering light management, water transport, salt rejection, durability, and economic feasibility rather than optical absorptivity alone.

3.4.1 Wick-assisted Photothermal Coatings

Wick-assisted absorbers employ porous materials that continuously transport saline water from the basin to the heated evaporation surface through capillary action. Materials including cotton fabric, jute, linen, carbon cloth, cellulose paper, and synthetic textiles have been widely investigated because they increase the effective evaporation area while reducing the thickness of the heated water layer (Murugavel *et al.* 2010; Lehmann and Joseph, 2015).

Experimental investigations generally report freshwater productivity improvements of 25–55% compared with conventional basin-type solar stills (Murugavel *et al.* 2010; Lehmann and Joseph, 2015). However, reported performance varies considerably because wick properties, including porosity, thickness, fiber orientation, hydrophilicity, and water retention capacity, strongly influence evaporation efficiency. In addition, differences in basin depth, solar irradiance, ambient temperature, and airflow further complicate direct comparison between studies.

While wick-assisted systems effectively enhance evaporation under controlled laboratory conditions, long-term operation introduces challenges associated with salt accumulation, biological fouling, and gradual degradation of natural fibers. These degradation mechanisms reduce capillary transport efficiency and eventually decrease freshwater productivity. Consequently, durability assessment should be regarded as equally important as initial thermal performance when evaluating wick materials for practical deployment.

3.4.2 Porous Carbon Foams and Three-dimensional Structures

Three-dimensional porous carbon materials, including carbon foams, carbon sponges, expanded graphite, and porous biochar, have attracted considerable attention because they integrate photothermal conversion with efficient thermal insulation (Ahmad *et al.* 2014; Manokar *et al.* 2018). Their interconnected pore networks promote multiple internal reflections of incident solar radiation, increasing photon residence time and improving overall solar absorption. At the same time, the low thermal conductivity of the porous matrix suppresses heat transfer to the underlying bulk water, thereby increasing the proportion of absorbed energy available for evaporation.

Several investigations have demonstrated productivity improvements exceeding 40% using porous carbon architectures (Ahmad *et al.* 2014; Manokar *et al.* 2018). Nevertheless, these improvements depend strongly on pore size distribution, density, wettability, and structural integrity. Highly porous materials generally provide superior thermal localization but may exhibit reduced mechanical strength, making them susceptible to compression, fracture, or deformation during prolonged operation.

Another important consideration is fabrication reproducibility. Many laboratory studies prepare porous carbon structures using carefully controlled carbonization and activation processes that are difficult to replicate consistently at industrial scale. Therefore, future research could focus on scalable manufacturing methods that produce uniform pore structures while keeping production costs low.

3.4.3 Bio-inspired and Natural Porous Materials

Inspired by natural water transport systems, researchers have increasingly investigated bio-based porous materials including wood, bamboo, loofah sponge, cellulose aerogels, and agricultural fibers as sustainable photothermal absorbers (Ahmad *et al.* 2014; Manokar *et al.* 2018). These materials naturally possess hierarchical pore networks that facilitate water transport while minimizing conductive heat losses.

Compared with synthetic porous materials, bio-inspired absorbers offer several practical advantages, including low density, biodegradability, widespread availability, and reduced environmental impact. In addition, many agricultural residues require only minimal processing before use, making them attractive for decentralized freshwater production in developing regions.

However, biological materials also present several limitations. Their structural properties vary by species, moisture content, age, and processing method, resulting in inconsistent thermal performance across studies. Furthermore, prolonged exposure to moisture and elevated temperature may promote microbial growth, biodegradation, or dimensional instability unless protective surface treatments are employed.

Consequently, although bio-inspired absorbers represent an environmentally attractive alternative, improvements in durability and material standardization remain necessary before large-scale implementation can be recommended.

3.4.4 Salt Management and Fouling Resistance

Salt accumulation remains one of the principal factors limiting the long-term performance of porous photothermal absorbers. Continuous evaporation concentrates dissolved salts near the heated surface, eventually leading to crystallization within surface pores. Progressive pore blockage reduces capillary water transport, decreases evaporation area, and lowers photothermal efficiency (Al-Karaghouli and Kazmerski, 2013; Velmurugan *et al.* 2008b; Manikandan *et al.* 2013).

Several design strategies have been proposed to mitigate salt accumulation, including asymmetric pore structures, directional water transport channels, hydrophilic surface modification, and self-floating evaporator configurations (Velmurugan *et al.* 2008b; Manikandan *et al.* 2013). Although these approaches have shown promising laboratory performance, relatively few investigations have evaluated their effectiveness during extended outdoor operation under natural seawater conditions.

Biofouling presents an additional challenge. The accumulation of microorganisms, algae, and organic matter may reduce optical absorption while obstructing water transport pathways. Coatings incorporating photocatalytic materials such as TiO_2 or antimicrobial additives have demonstrated improved resistance to biological contamination; however, their long-term environmental impacts and cost-effectiveness require further evaluation (Kabeel *et al.* 2014b; Manikandan *et al.* 2013).

3.4.5 Durability, Scalability and Economic Considerations

Despite impressive laboratory performance, relatively limited information is available regarding the long-term durability of porous absorber systems. Most published investigations evaluate thermal performance for less than 60–90 days, providing insufficient evidence concerning coating stability throughout the operational lifetime expected for commercial solar stills (Al-Karaghouli and Kazmerski, 2013; Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995).

Mechanical degradation from repeated wetting-drying cycles, ultraviolet exposure, thermal expansion, and salt crystallization remains a major concern. Furthermore, many porous materials require careful handling because their low density often reduces mechanical strength.

From an economic perspective, porous absorbers fabricated from biomass-derived materials generally offer substantial cost advantages over engineered nanomaterials. Their raw materials are inexpensive, widely available, and frequently derived from agricultural waste streams. Nevertheless, processing costs associated with carbonization, activation, freeze-drying, or chemical modification may increase manufacturing expenses depending on the preparation technique.

Therefore, future techno-economic analyses should evaluate not only material cost but also fabrication energy, expected service life, maintenance requirements, and replacement frequency to determine the true economic viability of porous absorber technologies.

3.4.6 Critical Assessment of Porous and Wick-assisted Coatings

Porous and wick-assisted absorber coatings are among the most promising directions for improving passive solar still performance because they enhance solar energy utilization through localized heating, efficient capillary water transport, and reduced conductive heat losses. Compared with conventional dense absorber coatings, these materials frequently achieve higher freshwater productivity while requiring relatively simple system modifications.

However, the literature also demonstrates that their reported advantages depend strongly on experimental configuration, pore architecture, environmental conditions, and durability. Many investigations emphasize short-term productivity gains but provide limited information on salt accumulation, structural degradation, fouling resistance, or long-term field performance.

Among currently available technologies, porous carbon materials and engineered biochar structures appear particularly attractive because they combine high photothermal efficiency with relatively low cost and environmental sustainability. Nevertheless, widespread commercialization will require standardized durability testing, scalable manufacturing methods, and comprehensive life-cycle assessments.

Future investigations could therefore prioritize long-term outdoor validation using natural saline water under standardized operating conditions while integrating thermal performance, durability, maintenance requirements, and economic analysis into a unified evaluation framework (Murugavel *et al.* 2010; Ahmad *et al.* 2014; Manokar *et al.* 2018; Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995; Al-Karaghouli and Kazmerski, 2013; Lehmann and Joseph, 2015; Velmurugan *et al.* 2008; Manikandan *et al.* 2013).

3.5 Sustainable Waste-derived Absorber Coatings

The increasing emphasis on sustainable materials and circular economy principles has stimulated considerable interest in waste-derived photothermal coatings for solar desalination. Unlike engineered nanomaterials that often require energy-intensive synthesis and expensive precursors, waste-derived coatings utilize readily available industrial, agricultural, or municipal waste streams to produce efficient absorber surfaces with significantly lower environmental and economic costs (Ahmad *et al.* 2014; Manokar *et al.* 2018;

Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995; Carlsson *et al.* 2000; Sampathkumar *et al.* 2010; Al-Karaghouli and Kazmerski, 2013; Hasson *et al.* 1968; Wang *et al.* 2014; Velmurugan *et al.* 2008; Manikandan *et al.* 2013). These materials not only improve solar still performance but also support waste valorization, resource conservation, and reduced greenhouse gas emissions associated with material production.

Recent investigations suggest that waste-derived absorber coatings can achieve thermal performance comparable to several conventional absorber materials while offering distinct advantages in terms of affordability and environmental sustainability. Nevertheless, their practical implementation depends on consistent material quality, long-term durability, and standardized fabrication methods.

3.5.1 Biochar-based Absorber Coatings

Biochar has emerged as one of the most promising sustainable photothermal materials because of its highly porous microstructure, broad-spectrum solar absorption, and low production cost. Produced through the pyrolysis of agricultural residues under oxygen-limited conditions, biochar converts biomass waste into a functional carbon material suitable for solar energy applications (Ahmad *et al.* 2014; Manokar *et al.* 2018).

Experimental studies have reported freshwater productivity improvements generally ranging from 30% to 45%, depending on feedstock type, pyrolysis temperature, activation process, and coating thickness (Ahmad *et al.* 2014; Manokar *et al.* 2018). The interconnected pore network of biochar enhances photon trapping while simultaneously reducing conductive heat losses to the bulk water. In addition, the porous structure promotes intimate contact between the heated absorber surface and the thin water film, improving evaporation efficiency.

Despite these advantages, direct comparison among published studies remains difficult because biochar properties vary considerably with biomass source. Rice husk, coconut shell, sugarcane bagasse, sawdust, and other agricultural residues produce biochars with different carbon content, ash composition, pore structure, and thermal conductivity. Consequently, reported performance reflects not only the intrinsic characteristics of biochar but also the influence of feedstock selection and processing conditions.

Future investigations should therefore establish standardized characterization procedures, including surface area, pore size distribution, optical absorptivity, and mechanical adhesion, to facilitate meaningful comparison among biochar-based coatings.

3.5.2 Waste Toner and Carbon-rich Industrial Residues

Waste toner powder recovered from discarded laser printer cartridges has recently attracted attention as an inexpensive photothermal coating because of its high carbon content, fine particle size, and strong optical absorption (Carlsson *et al.* 2000; Sampathkumar *et al.* 2010). Several laboratory investigations have demonstrated that properly processed waste toner coatings can improve absorber performance while significantly reducing coating cost.

Compared with commercially manufactured nanomaterials, waste toner requires minimal additional processing before application. However, toner composition varies among manufacturers and frequently contains polymeric binders, metal oxides, pigments, and trace additives. This variability complicates reproducibility and may influence long-term thermal stability.

Environmental safety also requires careful consideration. Certain toner formulations may contain heavy metals or organic additives that could be released through coating degradation during prolonged exposure to saline water. Accordingly, future evaluations of waste toner-based coatings could include leaching behavior and environmental risk assessments before considering large-scale deployment.

3.5.3 Fly Ash, Industrial By-products and Mineral Waste

Researchers have also explored industrial by-products such as fly ash, furnace slag, red mud, and mineral processing residues as low-cost photothermal materials because they contain thermally stable metal oxides and dark-colored mineral phases that absorb solar radiation (Hasson *et al.* 1968; Wang *et al.* 2014).

The principal advantage of these materials lies in their extremely low cost and widespread availability, particularly in regions with significant industrial activity. Nevertheless, their optical performance is generally lower than that of carbon-rich materials because many mineral residues exhibit comparatively lower solar absorptivity.

Another important limitation concerns material composition. Industrial residues often vary substantially depending on raw materials and manufacturing processes. In addition, some wastes may contain hazardous elements that require stabilization before environmental use. Consequently, comprehensive chemical characterization and environmental compliance testing should precede practical application.

Rather than serving as stand-alone absorber coatings, these materials may prove more suitable as fillers within composite photothermal coatings, where they provide mechanical stability while carbonaceous components enable efficient solar absorption.

3.5.4 Agricultural Residues and Biomass-derived Composites

Agricultural residues including rice husk, wheat straw, coconut shell, corn stalk, bamboo waste, cotton waste, and sawdust have become attractive precursors for sustainable absorber coatings because they are abundant, renewable, and inexpensive (Ahmad *et al.* 2014; Manokar *et al.* 2018). Through controlled carbonization or activation, these materials can be converted into porous carbon structures possessing excellent photothermal characteristics.

Compared with synthetic nanomaterials, biomass-derived coatings generally require lower production energy and exhibit reduced environmental impact throughout their life cycle. Their utilization simultaneously addresses waste management challenges while producing value-added materials for renewable energy applications.

However, biomass-derived absorbers also present challenges related to feedstock heterogeneity, seasonal availability, moisture sensitivity, and variable mechanical properties. Consequently, establishing quality-control standards for biomass processing represents an essential prerequisite for commercial implementation.

3.5.5 Sustainability and Life-cycle Considerations

While thermal efficiency remains an important performance indicator, sustainable absorber materials should also be evaluated from a broader life-cycle perspective. Parameters including embodied energy, carbon footprint, recyclability, environmental toxicity, raw material availability, and end-of-life disposal significantly influence the overall sustainability of coating technologies (Betz *et al.* 2010; Plueddemann, 1991; Lee *et al.* 2007).

Waste-derived coatings generally exhibit clear environmental advantages because they utilize existing waste streams rather than requiring extraction of virgin raw materials. Moreover, local production using regionally available biomass or industrial waste can reduce transportation costs and improve accessibility for remote communities.

Nevertheless, sustainability claims should be supported by quantitative life-cycle assessment (LCA) rather than qualitative discussion alone. At present, relatively few studies have evaluated the environmental performance of absorber coatings using standardized LCA methodologies, representing an important research gap identified in this review.

3.5.6 Techno-economic Assessment

Economic feasibility remains a principal advantage of waste-derived coatings. Their raw material cost is typically negligible compared with engineered nanomaterials such as graphene or carbon nanotubes. Consequently, even when thermal performance is slightly lower, their durability-adjusted cost per liter of freshwater may be substantially more favorable (Hischier and Walser, 2012; Poland *et al.* 2008; Roes *et al.* 2007).

However, coating economics should not be evaluated solely on material price. Processing energy, fabrication complexity, expected service life, maintenance frequency, and replacement costs all contribute to overall system economics. Some waste-derived materials require activation, grinding, chemical treatment, or controlled pyrolysis, which increases production costs.

Therefore, future techno-economic studies could use standardized economic indicators, including durability-adjusted cost per liter (CPL), levelized freshwater production cost, and life-cycle cost analysis, to enable meaningful comparisons among absorber technologies.

3.5.7 Critical Assessment of Waste-derived Coatings

Waste-derived absorber coatings represent one of the most promising directions for sustainable solar desalination because they integrate renewable energy production with resource recovery and circular economy principles. Compared with advanced nanomaterials, these coatings generally provide a more favorable balance among thermal performance, cost, scalability, and environmental sustainability.

Nevertheless, the available literature remains dominated by short-term laboratory studies employing different feedstocks, preparation methods, and testing conditions. Such methodological diversity limits direct comparison and hinders identification of the most suitable materials for practical deployment.

Among currently available waste-derived materials, biochar appears particularly promising because it combines excellent photothermal properties with low cost, abundant availability, and relatively simple fabrication. However, commercialization will require standardized manufacturing procedures, long-term durability evaluation, environmental safety assessment, and comprehensive life-cycle analysis.

Future research should therefore emphasize field-scale validation under natural climatic conditions, harmonized testing protocols, and integrated environmental and economic assessments to support the large-scale adoption of sustainable absorber coatings in decentralized solar desalination systems.

4. COMPARATIVE ASSESSMENT AND FUTURE PERSPECTIVES

4.1 Comparative Thermal Performance of Absorber Coatings

The enhancement of freshwater productivity in passive solar stills depends not only on the intrinsic optical properties of absorber coatings but also on their interaction with system design, environmental conditions, and operational parameters. Although numerous studies have reported significant improvements in evaporation rate and distillate yield after modifying absorber surfaces, direct comparison of published results remains challenging because experimental methodologies vary considerably. Parameters such as solar irradiance, ambient temperature, wind velocity, basin geometry, water depth, salinity, absorber material, coating thickness, and testing duration differ substantially among investigations, introducing variability that often exceeds the influence of the coating material itself.

Consequently, the thermal performance of absorber coatings should be evaluated using a comparative framework that considers both material characteristics and testing conditions rather than relying solely on reported percentage improvements in freshwater productivity. This approach provides a more realistic assessment of coating effectiveness and helps identify technologies with genuine potential for large-scale deployment.

4.1.1 Comparative Performance of Different Coating Categories

The absorber coatings reviewed in Section 3 demonstrate distinct advantages and limitations depending on their optical properties, thermal conductivity, and heat-transfer mechanisms. Carbon-based coatings generally exhibit the highest solar absorptivity because of their broadband light absorption and efficient photothermal conversion. Graphene and carbon nanotube coatings often achieve productivity improvements beyond conventional black-painted absorbers, mainly because their nanostructured morphology enhances photon absorption and enables rapid heat transfer within the absorber layer (Shanmugan *et al.* 2012; Kabeel *et al.* 2014a; Elango *et al.* 2015; Sharshir *et al.* 2017b). However, their superior laboratory performance is often accompanied by higher material costs, dispersion challenges, and limited long-term durability data.

Metal oxide coatings, particularly CuO and Fe_3O_4, provide a more balanced combination of optical performance, chemical stability, and economic feasibility (Sathyamurthy *et al.* 2014; Elango and Kalidasa, 2015; Omara *et al.* 2015; Sharshir *et al.* 2016; Chen and Mao, 2007; Kabeel *et al.* 2014; Nguyen *et al.* 2013; Rashidi *et al.* 2017; Kabeel *et al.* 2019; Atkinson *et al.* 2015; McDonald, 1975). Although their reported productivity improvements are generally lower than those of graphene-based coatings, their lower production cost, greater oxidation resistance, and compatibility with conventional coating techniques make them more attractive for practical implementation. Titanium dioxide coatings, while offering relatively modest photothermal performance, provide additional advantages through photocatalytic self-cleaning and improved resistance to surface fouling, which may support more stable long-term operation (Kabeel *et al.* 2014b; Nguyen *et al.* 2013).

Selective absorber coatings represent the most optically efficient surfaces because they combine high solar absorptivity with low infrared emissivity (Kumar and Tiwari, 2009; Cao *et al.* 2014; Zhang *et al.* 1996; Barshilia *et al.* 2011; Chen *et al.* 2017; Minasian and Al-Karaghouli, 1995; Sakthivel *et al.* 2010; Velmurugan *et al.* 2008a). Nevertheless, their benefits become less pronounced in passive solar stills operating below approximately 80 °C, where evaporative and convective heat losses dominate the thermal balance. Consequently, the productivity improvements reported for selective coatings are often smaller than those observed in conventional solar thermal collectors, despite their superior optical characteristics.

Porous and wick-assisted photothermal coatings improve freshwater production through a different mechanism. Rather than simply increasing absorber temperature, they localize thermal energy at the evaporation interface while continuously supplying water through capillary transport (Murugavel *et al.* 2010; Al-Karaghouli and Kazmerski, 2013; Lehmann and Joseph, 2015; Velmurugan *et al.* 2008; Manikandan *et al.* 2013). This interfacial heating strategy minimizes conductive heat losses to the bulk water and frequently produces higher evaporation efficiency than dense absorber surfaces under comparable solar irradiance. However, long-term performance depends strongly on pore architecture, water transport efficiency, and resistance to salt accumulation.

Waste-derived photothermal coatings, including biochar and other carbon-rich recycled materials, generally provide thermal performance approaching that of several engineered nanomaterials while substantially reducing material cost and environmental impact (Ahmad *et al.* 2014; Manokar *et al.* 2018; Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995; Carlsson *et al.* 2000; Sampathkumar *et al.* 2010; Al-Karaghouli and Kazmerski, 2013; Hasson *et al.* 1968; Wang *et al.* 2014; Velmurugan *et al.* 2008; Manikandan *et al.* 2013). Although their maximum productivity enhancement may be slightly lower than that of advanced nanocomposites, their favorable cost-to-performance ratio and sustainability make them particularly attractive for decentralized desalination systems.

4.1.2 Factors Contributing to Performance Variability

One of the principal findings of this review is that the wide variation in reported productivity improvements cannot be explained solely by coating composition. Instead, performance is governed by the combined influence of material properties and experimental conditions. For example, increasing solar irradiance enhances absorber temperature regardless of coating type, while shallow water depth reduces the thermal mass requiring heating and consequently increases evaporation rate.

Similarly, coating thickness influences both optical absorption and thermal resistance. Thin coatings may not provide complete surface coverage, whereas excessively thick coatings increase conductive resistance and may reduce overall heat transfer. The optimum coating thickness therefore depends on the thermal conductivity of the coating material, particle morphology, and deposition method.

Substrate material also plays an important role. Copper and aluminum substrates generally distribute absorbed heat more efficiently than stainless steel because of their higher thermal conductivity. Consequently, comparisons among different coating materials should account for substrate selection in addition to coating composition.

Environmental conditions further complicate comparison among published studies. Ambient temperature, wind speed, humidity, and seasonal variation all influence convective and evaporative heat losses. Therefore, productivity values reported under different climatic conditions should not be interpreted as direct indicators of coating superiority.

4.1.3 Normalization of Reported Performance

To facilitate meaningful comparison among absorber technologies, future investigations should adopt standardized testing protocols and normalized performance metrics. Rather than reporting freshwater productivity alone, studies should include operating conditions such as average solar irradiance, basin water depth, ambient temperature, wind speed, and salinity. Performance indicators normalized to incident solar energy, absorber area, and testing duration would allow more objective comparison across different investigations.

In addition, uncertainty analysis and statistical evaluation should become routine practice. Many published studies report single productivity values without confidence intervals or repeatability analysis, making it difficult to distinguish genuine performance improvements from experimental variability. Adoption of standardized reporting procedures would substantially improve the reliability of comparative assessments.

4.1.4 Comparative Assessment and Practical Implications

Fig. 2 shows the productivity improvements with different coatings. The literature indicates that no single absorber coating simultaneously optimizes thermal performance, durability, manufacturing cost, environmental sustainability, and scalability. Instead, each coating category presents distinct trade-offs that should be considered according to the intended application.

Graphene and carbon nanotube coatings show excellent photothermal performance but remain constrained by high production costs and limited evidence of long-term durability. Metal oxide coatings offer a more balanced combination of efficiency, stability, and affordability, whereas selective coatings provide superior optical characteristics but are less economically attractive for low-temperature solar still applications. Porous photothermal materials effectively enhance localized evaporation but require improved resistance to salt accumulation and mechanical degradation. Waste-derived coatings exhibit slightly lower maximum efficiency but provide outstanding sustainability, low cost, and high scalability.

These observations indicate that future absorber development should prioritize multifunctional hybrid coatings capable of integrating broadband solar absorption, efficient thermal localization, strong substrate adhesion, corrosion resistance, and environmentally sustainable fabrication within a single coating architecture.

4.1.5 Critical Perspective

Comparison of the available literature demonstrates that maximizing solar absorptivity alone is insufficient for achieving optimal solar still performance. The most successful absorber technologies are those that simultaneously improve heat localization, maintain long-term optical stability, resist degradation under saline conditions, and remain economically feasible for large-scale implementation. Consequently, future research should shift from maximizing short-term productivity enhancement toward developing robust coating systems that maintain stable performance throughout their operational lifetime.

Furthermore, standardized experimental methodologies, comparative testing under identical operating conditions, and durability-adjusted performance metrics are essential for identifying truly superior absorber technologies. Without such harmonization, differences in reported productivity will continue to reflect variations in experimental design rather than intrinsic coating performance, limiting the translation of laboratory advances into commercially viable solar desalination systems.

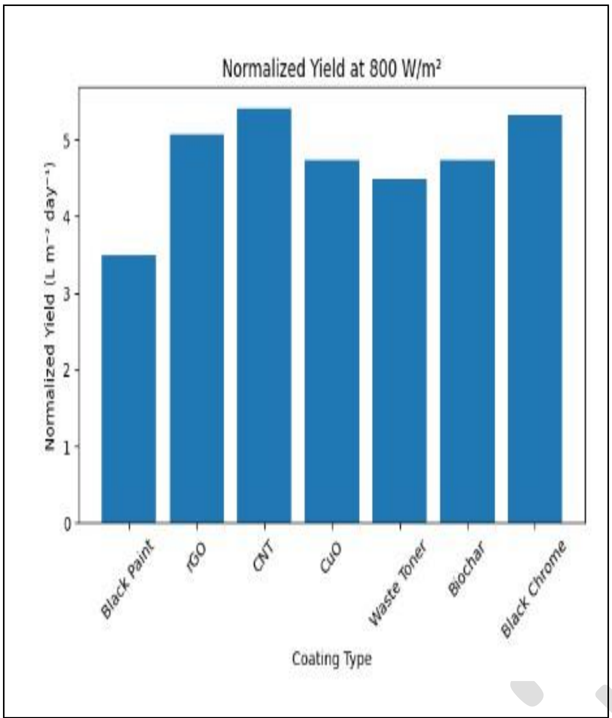

Fig. 2: Productivity improvements with different coatings

4.2 Durability and Long-term Stability of Absorber Coatings

While thermal efficiency is frequently reported as the primary performance indicator for absorber coatings, long-term durability ultimately determines the practical viability of solar still technologies. Coatings that exhibit excellent photothermal conversion during short-term laboratory experiments may experience significant deterioration when exposed to prolonged solar irradiation, saline water, thermal cycling, and environmental contaminants. Therefore, durability should be considered alongside optical performance when evaluating absorber materials for commercial solar desalination systems (Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995; Carlsson *et al.* 2000; Sampathkumar *et al.* 2010; Banerjee *et al.* 2015; Al-Karaghouli and Kazmerski, 2013; Hischier and Walser, 2012; Poland *et al.* 2008; Hasson *et al.* 1968; Wang *et al.* 2014; Betz *et al.* 2010; Plueddemann, 1991; Lee *et al.* 2007; Roes *et al.* 2007).

A critical assessment of the available literature indicates that durability has received considerably less attention than thermal performance. Most investigations focus on freshwater productivity measured over a few days or weeks, whereas relatively few studies examine coating behavior beyond two or three months of continuous operation. Consequently, reliable information regarding long-term service life, maintenance requirements, and failure mechanisms remains limited.

4.2.1 Degradation Mechanisms

Absorber coating degradation results from the combined effects of physical, chemical, and mechanical processes during prolonged exposure to outdoor operating conditions. These degradation mechanisms rarely act independently; instead, they interact to progressively reduce optical absorptivity, thermal conductivity, and coating adhesion.

Salt crystallization is one of the most common degradation mechanisms in passive solar stills. Continuous evaporation increases salt concentration near the heated absorber surface, eventually leading to crystal formation. Repeated crystallization and dissolution generate localized mechanical stresses that promote cracking, pore blockage, and coating delamination, particularly in porous and wick-assisted absorbers (Cao *et al.* 2014; Zhang *et al.* 1996; Barshilia *et al.* 2011; Chen *et al.* 2017; Minasian and Al-Karaghouli, 1995; Sakthivel *et al.* 2010; Velmurugan *et al.* 2008a). Carbon-based coatings with weak binder systems are especially susceptible to this type of degradation.

Thermal cycling represents another important factor affecting coating stability. Daily fluctuations between daytime heating and nighttime cooling produce repeated expansion and contraction of both the coating and substrate. Differences in their coefficients of thermal expansion generate interfacial stresses that gradually weaken adhesion and may eventually result in blistering or peeling (Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995). Thin-film coatings deposited by vacuum techniques generally exhibit better dimensional stability than thick paint-based coatings, although their performance depends strongly on deposition quality.

Ultraviolet radiation further accelerates coating degradation through photochemical reactions involving polymeric binders and organic additives. Carbon nanomaterials themselves exhibit excellent resistance to ultraviolet exposure; however, degradation of the surrounding binder matrix can reduce coating integrity and expose nanoparticles to mechanical loss. In contrast, metal oxide coatings, particularly TiO_2-based systems, generally demonstrate superior resistance to ultraviolet-induced degradation because of their inorganic composition (Kabeel *et al.* 2014b; Banerjee *et al.* 2015).

4.2.2 Corrosion and Chemical Stability

The chemical stability of absorber coatings is particularly important because solar stills operate continuously in chloride-rich saline environments that promote corrosion of metallic substrates. Corrosion not only reduces the structural integrity of the absorber plate but also weakens coating adhesion and alters optical properties.

Carbon-based coatings depend primarily on the corrosion resistance of the underlying substrate and protective binder. Inadequate sealing permits penetration of saline water to the metal–coating interface, initiating localized corrosion and subsequent coating failure (Kim *et al.* 2011; Kantesh, 2012). Surface functionalization and improved binder formulations have demonstrated enhanced corrosion resistance, although long-term field validation remains limited.

Metal oxide coatings generally exhibit superior chemical stability because many oxides, including CuO, TiO_2, and Fe_3O_4, are inherently resistant to oxidation and chloride attack (Sathyamurthy *et al.* 2014; Elango and Kalidasa, 2015; Omara *et al.* 2015; Sharshir *et al.* 2016; Chen and Mao, 2007; Kabeel *et al.* 2014; Nguyen *et al.* 2013; Rashidi *et al.* 2017; Kabeel *et al.* 2019; Atkinson *et al.* 2015; McDonald, 1975). Nevertheless, corrosion may still occur at defects, pinholes, or damaged coating regions where the metallic substrate becomes exposed.

Selective absorber coatings deposited by electroplating or vacuum deposition typically provide excellent corrosion resistance when coating integrity is maintained. However, localized mechanical damage may expose the underlying metal and accelerate corrosion beneath the coating, making defect prevention particularly important during manufacturing and installation.

4.2.3 Mechanical Integrity and Adhesion

Strong adhesion between the absorber coating and substrate is essential to maintain consistent thermal performance throughout the solar still's operational lifetime. Weak interfacial bonding promotes delamination during repeated wetting-drying cycles, thermal expansion, and mechanical cleaning.

Among the coating categories reviewed, graphene and carbon nanotube coatings often exhibit excellent intrinsic thermal properties but relatively poor adhesion unless appropriate surface functionalization or coupling agents are employed (Shanmugan *et al.* 2012; Kim *et al.* 2011; Elango *et al.* 2015). Agglomeration of nanomaterials may also reduce coating uniformity and create localized stress concentrations.

Conversely, conventional metal oxide coatings and commercially developed selective coatings generally display better adhesion because they are frequently deposited using controlled chemical or physical deposition techniques. However, these methods also increase fabrication complexity and production cost.

For porous and biomass-derived coatings, mechanical stability depends largely on pore architecture and binder composition. Highly porous structures provide efficient thermal localization but often possess lower compressive strength, increasing susceptibility to physical damage during long-term operation or maintenance.

4.2.4 Fouling, Scaling and Surface Contamination

Surface fouling significantly influences long-term absorber performance by reducing solar absorptivity and restricting heat transfer. Mineral scaling, biological growth, and deposition of suspended particulates gradually modify surface morphology and optical characteristics, reducing evaporation efficiency over time (Al-Karaghouli and Kazmerski, 2013; Velmurugan *et al.* 2008b; Manikandan *et al.* 2013).

Scaling is particularly problematic for porous absorbers because salt crystals may block capillary pathways, reducing water transport to the evaporation interface. Several investigations have proposed asymmetric pore structures and self-cleaning surface designs to improve salt rejection; however, experimental validation under prolonged exposure to natural seawater remains limited.

Biological fouling caused by algae, bacteria, and organic matter represents another challenge, particularly in systems using untreated surface water. Photocatalytic coatings incorporating TiO_2 have demonstrated the potential to reduce biological contamination through ultraviolet-induced oxidation of organic deposits (Kabeel *et al.* 2014b; Banerjee *et al.* 2015). Nevertheless, further investigation is needed to assess the effectiveness of these coatings under long-term outdoor conditions.

4.2.5 Durability versus Thermal Performance

A key observation from this review is that the coating with the highest initial thermal efficiency is not necessarily the most suitable for practical application. Several advanced nanomaterials provide outstanding short-term productivity enhancement but lack sufficient long-term durability data. Conversely, coatings with slightly lower thermal efficiency frequently demonstrate greater resistance to corrosion, mechanical degradation, and environmental exposure.

For example, graphene and carbon nanotube coatings consistently outperform many conventional materials under laboratory conditions, whereas biochar, CuO, and selective coatings often provide a more favorable balance between efficiency, durability, and economic feasibility. Consequently, absorber selection should be based on life-cycle performance rather than maximum short-term productivity alone.

Future studies could therefore evaluate coatings using durability-adjusted performance indicators that combine freshwater productivity with service life, maintenance frequency, and replacement requirements.

4.2.6 Research Needs and Future Directions

The review demonstrates a clear need for standardized durability evaluation protocols. Currently, differences in testing duration, saline composition, climatic conditions, and performance metrics make comparisons across published investigations difficult. Future studies should incorporate accelerated aging procedures that simulate ultraviolet exposure, thermal cycling, salt crystallization, humidity variation, and mechanical abrasion under controlled conditions.

In addition, outdoor field validation extending beyond one year should become an essential component of absorber coating development. Such investigations would provide valuable information regarding seasonal variability, maintenance requirements, coating degradation rates, and operational reliability under realistic environmental conditions.

Finally, future absorber technologies should prioritize multifunctional coating systems that combine high solar absorptivity with strong adhesion, corrosion resistance, self-cleaning capability, and environmentally sustainable fabrication. Hybrid composite coatings integrating carbon materials with corrosion-resistant metal oxides represent a particularly promising direction for achieving these objectives (Kim *et al.* 2011; Sathyamurthy *et al.* 2014; Elango and Kalidasa, 2015; Omara *et al.* 2015; Sharshir *et al.* 2016; Chen and Mao, 2007; Kabeel *et al.* 2014; Nguyen *et al.* 2013; Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995; Carlsson *et al.* 2000; Sampathkumar *et al.* 2010; Rashidi *et al.* 2017; Kabeel *et al.* 2019; Atkinson *et al.* 2015; McDonald, 1975; Banerjee *et al.* 2015; Al-Karaghouli and Kazmerski, 2013; Hischier and Walser, 2012; Poland *et al.* 2008; Hasson *et al.* 1968; Wang *et al.* 2014; Betz *et al.* 2010; Plueddemann, 1991; Lee *et al.* 2007; Roes *et al.* 2007).

Critical Perspective

Current research has successfully demonstrated substantial improvements in the initial thermal performance of absorber coatings; however, durability remains the principal barrier to commercialization. Most available studies provide only short-term laboratory evidence and therefore do not adequately represent the conditions experienced during long-term field operation. Establishing standardized durability testing procedures, integrating accelerated aging protocols, and adopting durability-adjusted performance metrics will be essential for identifying absorber coatings capable of supporting reliable, economically viable, and sustainable solar desalination systems.

4.3 Techno-economic Assessment and Commercialization Potential of Absorber Coatings

Although thermal performance is commonly used to evaluate absorber coatings in passive solar stills, commercial deployment depends equally on economic feasibility, manufacturing scalability, operational durability, and maintenance requirements. A coating that achieves high freshwater productivity under laboratory conditions may not necessarily be the most appropriate choice for large-scale implementation if it requires expensive raw materials, sophisticated fabrication techniques, or frequent replacement. Therefore, the selection of absorber coatings should be based on a comprehensive techno-economic assessment that considers the complete life-cycle cost of freshwater production rather than thermal efficiency alone.

The literature demonstrates that the relationship between coating performance and economic viability is not always proportional. In many cases, relatively inexpensive materials produce slightly lower thermal efficiencies while offering substantially lower production costs and greater long-term reliability. Consequently, identifying the optimum absorber coating requires balancing thermal performance with manufacturing complexity, durability, maintenance, and environmental sustainability.

4.3.1 Material Cost and Fabrication Complexity

The cost of absorber coatings varies considerably depending on raw material availability, synthesis method, and deposition technique. Carbon nanomaterials such as graphene and carbon nanotubes exhibit excellent photothermal performance but remain among the most expensive coating materials because of complex synthesis, purification, and dispersion processes (Shanmugan *et al.* 2012; Kim *et al.* 2011; Elango *et al.* 2015). Uniform coating deposition frequently requires ultrasonication, chemical functionalization, or specialized polymer binders, increasing both production cost and manufacturing complexity.

Metal oxide coatings, including CuO, TiO_2, and Fe_3O_4, provide a more economical alternative because their precursor materials are widely available and compatible with conventional fabrication techniques such as spray coating, dip coating, and sol-gel deposition (Sathyamurthy *et al.* 2014; Elango and Kalidasa, 2015; Omara *et al.* 2015; Sharshir *et al.* 2016; Chen and Mao, 2007; Kabeel *et al.* 2014; Nguyen *et al.* 2013; Rashidi *et al.* 2017; Kabeel *et al.* 2019; Atkinson *et al.* 2015; McDonald, 1975). These processes require less sophisticated equipment and are more suitable for industrial-scale manufacturing.

Selective absorber coatings generally involve vacuum deposition, magnetron sputtering, electroplating, or chemical vapor deposition (Zhu *et al.* 2018; Kumar and Tiwari, 2009; Cao *et al.* 2014; Zhang *et al.* 1996; Barshilia *et al.* 2011; Chen *et al.* 2017; Minasian and Al-Karaghouli, 1995; Sakthivel *et al.* 2010; Velmurugan *et al.* 2008; Xu *et al.* 2017; Ghasemi *et al.* 2014). Although these methods produce highly uniform coatings with excellent optical properties, they significantly increase manufacturing costs and require specialized infrastructure. Consequently, selective coatings may be economically justified for high-performance solar thermal collectors but are often less attractive for low-cost solar stills intended for decentralized freshwater production.

Waste-derived coatings, particularly biochar and recycled carbon materials, offer the lowest material costs because they utilize agricultural residues or industrial waste streams that are locally available in many regions (Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995; Carlsson *et al.* 2000; Sampathkumar *et al.* 2010; Al-Karaghouli and Kazmerski, 2013; Hasson *et al.* 1968; Wang *et al.* 2014; Velmurugan *et al.* 2008; Manikandan *et al.* 2013). However, processing steps such as carbonization, activation, grinding, or surface modification can influence the final production cost and should therefore be considered in economic evaluations.

4.3.2 Durability-adjusted Cost of Freshwater Production

Economic assessment based solely on initial material cost may be misleading because absorber coatings differ substantially in service life and maintenance requirements. Coatings requiring frequent repair or replacement may ultimately produce freshwater at a higher overall cost despite their low purchase price.

For this reason, durability-adjusted performance metrics provide a more meaningful basis for comparison. Indicators such as the cost per liter of freshwater (CPL), life-cycle cost (LCC), and levelized cost of water (LCOW) incorporate both capital expenditure and operational costs throughout the service life of the coating (Hischier and Walser, 2012; Poland *et al.* 2008; Betz *et al.* 2010; Plueddemann, 1991; Lee *et al.* 2007; Roes *et al.* 2007).

Although relatively few studies have reported standardized economic analyses, available evidence suggests that biochar-based coatings, CuO coatings, and conventional carbon black absorbers generally provide lower durability-adjusted costs than graphene or carbon nanotube coatings because of their lower material prices and simpler fabrication methods. Conversely, advanced nanocomposite coatings may justify their higher initial investment only if their superior thermal performance is maintained over prolonged operating periods without significant degradation.

Future studies should therefore report standardized economic indicators together with thermal performance to facilitate objective comparisons among absorber technologies.

4.3.3 Scalability and Manufacturing Readiness

The commercial potential of absorber coatings depends not only on laboratory performance but also on the feasibility of large-scale manufacturing. Several high-performing nanomaterial coatings remain difficult to reproduce consistently because their properties depend on precise nanoparticle dispersion, coating thickness, and substrate preparation.

Graphene and carbon nanotube coatings illustrate this challenge. While laboratory-scale deposition often achieves highly uniform coatings through controlled processing conditions, scaling these procedures to industrial production introduces difficulties related to agglomeration, quality control, and process reproducibility (Kim *et al.* 2011; Elango *et al.* 2015).

In contrast, conventional paint-based carbon coatings and many metal oxide coatings can be produced using well-established industrial coating technologies. Spray coating, dip coating, and roll-to-roll processing offer relatively inexpensive manufacturing routes compatible with large absorber surfaces.

Waste-derived materials also demonstrate strong scalability because their raw materials are widely available and often require only moderate processing before application. Their utilization additionally supports regional manufacturing and reduces dependence on imported advanced materials.

4.3.4 Maintenance and Operational Considerations

Operational costs are strongly influenced by coating durability and maintenance frequency. Surface degradation caused by salt crystallization, fouling, corrosion, ultraviolet exposure, and mechanical abrasion gradually reduces optical performance, requiring cleaning, repair, or replacement (Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995; Al-Karaghouli and Kazmerski, 2013; Velmurugan *et al.* 2008b; Manikandan *et al.* 2013).

Porous and wick-assisted coatings generally require more frequent maintenance because salt accumulation may obstruct capillary pathways and reduce evaporation efficiency. Similarly, natural biomass-derived materials may require periodic replacement owing to biological degradation under prolonged humid conditions.

Metal oxide and selective absorber coatings generally exhibit superior chemical stability and lower maintenance requirements, although mechanical damage may still necessitate localized repair. Carbon nanomaterial coatings require careful handling because mechanical abrasion or binder degradation may reduce coating integrity.

Consequently, techno-economic analyses should incorporate maintenance requirements rather than focusing only on initial productivity improvements.

4.3.5 Commercialization Prospects

The transition from laboratory-scale demonstrations to commercial solar desalination systems requires coating technologies that simultaneously satisfy performance, durability, affordability, environmental safety, and manufacturing scalability. Current evidence indicates that no single coating category fully meets all these criteria.

Graphene- and CNT-based coatings currently represent the highest-performing photothermal materials; however, their widespread commercialization remains constrained by high material costs, limited long-term durability data, and manufacturing challenges. Metal oxide coatings appear to offer the most favorable compromise between efficiency, durability, and industrial feasibility because they combine acceptable thermal performance with established manufacturing technologies.

Selective absorber coatings remain attractive for specialized high-performance applications where maximum thermal efficiency justifies increased production costs. In contrast, waste-derived photothermal coatings demonstrate particularly strong potential for decentralized rural desalination because of their low cost, environmental sustainability, and compatibility with circular economy principles.

Overall, hybrid composite coatings integrating carbon-based photothermal materials with corrosion-resistant metal oxides may represent the most promising pathway for future commercialization, provided that scalable fabrication methods and long-term durability can be demonstrated.

4.3.6 Future Directions for Techno-economic Evaluation

A major limitation identified in the current literature is the absence of standardized economic assessment methodologies. Most studies report freshwater productivity without evaluating the associated economic implications, making comparison among coating technologies difficult. Future investigations should therefore adopt harmonized evaluation frameworks incorporating:

- Capital cost of coating preparation;
- Material availability and supply-chain considerations;
- Fabrication energy requirements;
- Expected service life;
- Maintenance and replacement frequency;
- Life-cycle cost (LCC);
- Levelized cost of water (LCOW);
- Cost per liter of freshwater (CPL); and
- Environmental externalities and end-of-life management.

Integrating these indicators with thermal performance will provide a more comprehensive basis for selecting absorber coatings suitable for commercial deployment. Fig. 3 shows the durability-adjusted cost per liter (CPL) of common absorber coatings, highlighting differences in their overall economic performance. Waste-derived coatings, particularly waste toner and biochar, exhibit lower durability-adjusted costs, whereas rGO and CNT coatings show higher costs. These results demonstrate that waste-derived coatings may provide a more favorable economic balance when durability and service-life considerations are included alongside thermal performance.

Critical Perspective

The evidence reviewed indicates that maximizing freshwater productivity alone is insufficient for identifying commercially viable absorber coatings. Practical implementation requires technologies that maintain stable thermal performance over extended operating periods while remaining economically competitive and environmentally sustainable. Although advanced nanomaterials continue to dominate laboratory-scale performance, simpler carbon-based, metal oxide, and waste-derived coatings currently offer a more favorable balance between efficiency, durability, manufacturing simplicity, and cost. Future research could therefore prioritize durability-adjusted economic optimization rather than pursuing incremental improvements in short-term thermal efficiency alone.

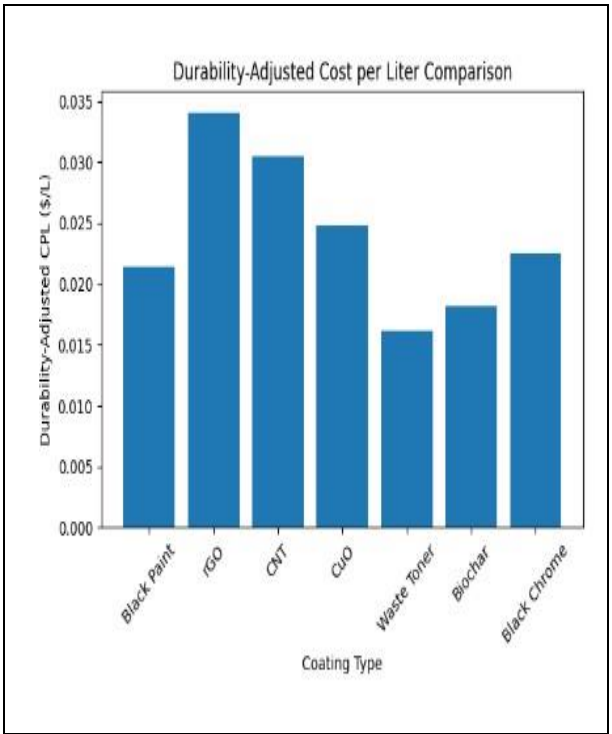

Fig. 3: Durability-adjusted cost-per-liter (CPL) comparison of common absorber coatings

4.4 Environmental Sustainability and Life-cycle Considerations of Absorber Coatings

The development of high-performance absorber coatings for passive solar stills should not be evaluated solely on the basis of thermal efficiency or freshwater productivity. Growing emphasis on sustainable engineering requires assessing coating technologies more broadly, including resource consumption, environmental impacts, manufacturing energy, operational safety, recyclability, and end-of-life management. Consequently, life-cycle thinking has become an essential component in the evaluation of photothermal materials for solar desalination systems (Hischier and Walser, 2012; Poland *et al.* 2008; Betz *et al.* 2010; Plueddemann, 1991; Lee *et al.* 2007; Roes *et al.* 2007; Kabeel and El-Agouz, 2011; Mahian *et al.* 2013).

Although solar stills inherently utilize renewable solar energy, the environmental footprint of the absorber coating itself may vary considerably depending on raw material extraction, synthesis routes, fabrication methods, operational durability, and disposal practices. Therefore, coating selection should balance thermal performance with environmental sustainability to ensure that improvements in freshwater production do not introduce disproportionate ecological burdens.

4.4.1 Environmental Impacts of Different Coating Categories

The environmental performance of absorber coatings differs significantly among the major material classes discussed in Section 3.

Carbon-based nanomaterials, including graphene and carbon nanotubes, provide exceptional photothermal performance but generally require energy-intensive synthesis techniques, chemical purification, and specialized processing. These manufacturing steps increase embodied energy and may involve hazardous chemicals or solvents if appropriate waste-management practices are not implemented (Shanmugan *et al.* 2012; Wang *et al.* 2008; Elango *et al.* 2015). Furthermore, large-scale production of advanced nanocarbons remains associated with relatively high environmental and economic costs.

Metal oxide coatings generally exhibit lower environmental burdens because many precursor materials, such as titanium dioxide, iron oxide, and copper oxide, are naturally abundant and can be synthesized using comparatively mature industrial processes (Sathyamurthy *et al.* 2014; Elango and Kalidasa, 2015; Omara *et al.* 2015; Sharshir *et al.* 2016; Chen and Mao, 2007; Kabeel *et al.* 2014; Nguyen *et al.* 2013; Rashidi *et al.* 2017; Kabeel *et al.* 2019; Atkinson *et al.* 2015; McDonald, 1975). However, mining, chemical processing, and nanoparticle production still consume significant energy and water resources. Sustainable production strategies should therefore prioritize low-temperature synthesis methods and reduced chemical consumption.

Selective absorber coatings fabricated by vacuum deposition or electrochemical processing often require specialized equipment operating under controlled conditions, resulting in relatively high energy demand during manufacturing (Zhu *et al.* 2018; Kumar and Tiwari, 2009; Cao *et al.* 2014; Zhang *et al.* 1996; Barshilia *et al.* 2011; Chen *et al.* 2017; Minasian and Al-Karaghouli, 1995; Sakthivel *et al.* 2010; Velmurugan *et al.* 2008; Xu *et al.* 2017; Ghasemi *et al.* 2014). While their long service life partially offsets this initial environmental cost, comprehensive life-cycle assessments remain limited.

In contrast, waste-derived absorber coatings, including biochar, recycled carbon materials, and agricultural biomass, offer clear environmental advantages by utilizing existing waste streams and reducing dependence on virgin raw materials (Ahmad *et al.* 2014; Manokar *et al.* 2018; Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995; Carlsson *et al.* 2000; Sampathkumar *et al.* 2010; Al-Karaghouli and Kazmerski, 2013; Hasson *et al.* 1968; Wang *et al.* 2014; Velmurugan *et al.* 2008; Manikandan *et al.* 2013). These materials contribute to circular economy principles by converting agricultural residues and industrial by-products into functional photothermal materials while simultaneously reducing landfill disposal and open-field burning.

4.4.2 Nanoparticle Release and Environmental Safety

The growing application of nanostructured coatings raises concerns regarding the potential release of nanoparticles during fabrication, operation, maintenance, or disposal. Mechanical abrasion, ultraviolet degradation, thermal cycling, and coating delamination may gradually release nanoscale particles into surrounding soil or water (Wang *et al.* 2016; Kabeel and El-Agouz, 2011; Mahian *et al.* 2013).

Although current evidence indicates that absorber coatings generally remain strongly attached under normal operating conditions, relatively few investigations have quantified nanoparticle leaching during prolonged saline exposure. This represents an important knowledge gap because released nanoparticles may accumulate within aquatic environments or enter the food chain.

Environmental risk depends on material composition. Carbon nanotubes and graphene possess unique physicochemical properties that warrant careful evaluation of occupational exposure during manufacturing. Similarly, certain metal oxide nanoparticles may exhibit ecotoxicological effects at elevated concentrations despite their generally favorable chemical stability.

Future coating development should therefore emphasize environmentally benign binders, strong interfacial adhesion, and low-emission fabrication techniques while incorporating standardized nanoparticle release testing into durability assessments.

4.4.3 Circular Economy and Resource Efficiency

Circular economy principles encourage recovering and reusing materials throughout their life cycle to minimize resource depletion and waste generation. Waste-derived absorber coatings represent one of the most promising approaches for integrating renewable energy production with sustainable waste management (Ahmad *et al.* 2014; Manokar *et al.* 2018; Kantesh, 2012; Hutchinson and Suo, 1991; Freund and Suresh, 2003; Rabek, 1995; Carlsson *et al.* 2000; Sampathkumar *et al.* 2010; Al-Karaghouli and Kazmerski, 2013; Hasson *et al.* 1968; Wang *et al.* 2014; Velmurugan *et al.* 2008; Manikandan *et al.* 2013).

Agricultural residues such as rice husk, coconut shell, sugarcane bagasse, sawdust, and bamboo waste can be converted into porous carbon materials through controlled carbonization, creating high-value photothermal absorbers from otherwise discarded biomass. Similarly, recycled carbon powders and selected industrial by-products reduce reliance on newly manufactured materials while lowering overall production costs.

Beyond reducing environmental impacts, localized production using regionally available waste materials can strengthen rural supply chains, decrease transportation-related emissions, and improve the affordability of solar desalination technologies in water-scarce communities. Nevertheless, consistent quality control remains essential because waste-derived feedstocks often vary significantly in chemical composition and physical properties.

4.4.4 Life-cycle Assessment of Absorber Coatings

Life-cycle assessment (LCA) provides a systematic framework for quantifying the environmental impacts associated with material production, use, and disposal. Despite its importance, relatively few studies have applied standardized LCA methodologies specifically to absorber coatings used in passive solar stills (Betz *et al.* 2010; Plueddemann, 1991; Lee *et al.* 2007; Roes *et al.* 2007).

Most published investigations emphasize thermal performance while providing limited information regarding embodied energy, greenhouse gas emissions, water consumption during fabrication, recyclability, or end-of-life treatment. Consequently, comparisons among coating technologies remain incomplete because environmental performance is seldom evaluated alongside thermal efficiency.

Future LCAs should include the following stages:

- Raw material extraction and processing;
- Coating synthesis and fabrication;
- Transportation and installation;
- Operational lifetime and maintenance;
- Coating replacement frequency;
- Recycling, reuse, or disposal; and
- Potential environmental emissions during service.

Integrating these parameters with productivity data would provide a more comprehensive basis for selecting absorber materials that are both technically effective and environmentally sustainable.

4.4.5 Sustainability-performance Trade-offs

The comparative analysis presented in this review indicates that the absorber coating with the highest thermal efficiency is not always the most sustainable option. Advanced nanomaterials frequently deliver superior photothermal conversion but require greater manufacturing energy and higher economic investment. Conversely, waste-derived carbon materials may provide slightly lower productivity while significantly reducing environmental impacts and improving resource efficiency.

Similarly, selective absorber coatings possess excellent optical characteristics and long operational lifetimes but generally involve energy-intensive manufacturing processes. Metal oxide coatings occupy an intermediate position by offering acceptable thermal performance together with relatively mature manufacturing technologies and good durability.

These observations suggest that future absorber development should focus on optimizing the balance among thermal efficiency, durability, environmental impact, and economic feasibility rather than maximizing any single performance criterion.

4.4.6 Future Perspectives for Sustainable Coating Development

Future research could adopt multidisciplinary design strategies that integrate materials science, environmental engineering, and life-cycle analysis. Several research priorities emerge from the present review.

First, standardized environmental assessment methodologies should accompany thermal performance evaluation to enable objective comparison among absorber technologies. Second, coating formulations should prioritize renewable and low-toxicity precursor materials while minimizing hazardous solvents and chemical additives. Third, long-term studies investigating nanoparticle release, degradation products, and environmental exposure under realistic operating conditions are required to support safe commercialization.

Finally, hybrid coatings incorporating renewable carbon materials with chemically stable metal oxides offer considerable promise because they combine high photothermal efficiency with improved durability and reduced environmental impact. Such multifunctional materials may provide the most practical pathway toward sustainable solar desalination technologies.

Critical Perspective

The future development of absorber coatings should be guided by life-cycle sustainability rather than thermal performance alone. While advanced nanomaterials continue to demonstrate excellent laboratory efficiencies, their environmental and economic implications require more comprehensive evaluation before large-scale deployment. Waste-derived photothermal materials and environmentally benign hybrid coatings appear particularly promising because they align renewable energy generation with circular economy principles and sustainable resource management. Incorporating standardized life-cycle assessment, environmental safety evaluation, and recyclability analysis into future absorber coating research will strengthen the transition from laboratory innovation to commercially viable and environmentally responsible solar desalination systems.

5. CONCLUSION AND FUTURE OUTLOOK

5.1 Major Findings

This review critically evaluated the role of absorber coatings in improving the thermal performance and freshwater productivity of passive solar stills by examining recent advances in carbon-based materials, metal oxide coatings, selective absorber surfaces, porous photothermal structures, and sustainable waste-derived coatings. The comparative analysis demonstrates that absorber coatings influence solar still performance through multiple mechanisms, including enhanced solar absorptivity, improved thermal localization, reduced radiative and conductive heat losses, optimized water transport, and increased evaporation efficiency. However, the effectiveness of each coating category depends not only on its intrinsic material properties but also on operating conditions, fabrication quality, and long-term stability.

Carbon-based coatings, particularly graphene and carbon nanotubes, consistently exhibit excellent photothermal conversion because of their broadband solar absorption, high thermal conductivity, and nanoscale heat-transfer characteristics. Nevertheless, their widespread application remains constrained by relatively high production costs, challenges in achieving uniform dispersion and adhesion, and limited evidence regarding long-term durability under saline operating conditions. Consequently, despite their superior laboratory performance, further work is required before these materials can be considered commercially viable for large-scale solar desalination.

Metal oxide coatings provide a more balanced combination of thermal performance, chemical stability, corrosion resistance, and manufacturing feasibility. Materials such as CuO, TiO_2, and Fe_3O_4 generally deliver reliable improvements in freshwater productivity while remaining compatible with scalable coating techniques. In addition to their photothermal properties, selected metal oxides offer supplementary functions, including photocatalytic self-cleaning and anti-fouling behaviour, which may improve long-term operational stability. These characteristics position metal oxide coatings as practical candidates for field implementation where durability and cost are important considerations.

Selective absorber coatings remain among the most optically efficient surface treatments because they combine high solar absorptivity with low thermal emissivity. However, the review indicates that their advantages become less pronounced in passive solar stills, where operating temperatures are relatively low and evaporative heat transfer dominates the overall energy balance. As a result, the added manufacturing complexity and cost of advanced selective coatings are not always justified for low-temperature desalination systems.

Porous and wick-assisted photothermal coatings represent a significant advancement in solar desalination because they promote localized interfacial heating and continuous capillary water transport. By concentrating thermal energy at the evaporation interface rather than heating the entire water volume, these materials improve the utilization of absorbed solar energy. Despite these advantages, long-term performance depends strongly on pore architecture, salt accumulation, fouling, and mechanical stability, underscoring the need for extended durability evaluation under realistic environmental conditions.

Among the coating categories reviewed, waste-derived photothermal materials offer one of the most attractive combinations of performance, affordability, and environmental sustainability. Biochar, agricultural residues, and recycled carbon materials show that effective absorber coatings can be produced from low-cost, renewable resources while supporting circular economy principles. Although these materials generally exhibit slightly lower peak efficiencies than advanced nanomaterials, their favorable cost-to-performance ratio, local availability, and reduced environmental footprint make them particularly suitable for decentralized freshwater production in resource-constrained regions.

A key finding of this review is that reported improvements in freshwater productivity should be interpreted with caution, as direct comparison among published studies is complicated by substantial differences in experimental methodology. Variations in solar irradiance, basin geometry, water depth, salinity, climatic conditions, coating thickness, and testing duration frequently influence system performance to a degree comparable with the coating material itself. Therefore, the absence of standardized testing protocols remains a significant limitation in the current literature and hinders objective evaluation of absorber technologies.

The review also demonstrates that thermal efficiency alone is an insufficient criterion for selecting absorber coatings. Practical implementation requires considering durability, corrosion resistance, mechanical adhesion, environmental impact, manufacturing scalability, maintenance requirements, and life-cycle cost. When these broader criteria are considered collectively, materials offering moderate thermal improvements but superior durability and affordability may provide greater long-term value than coatings delivering higher short-term efficiency under laboratory conditions.

Overall, the evidence indicates that no single coating technology currently satisfies all the requirements for high-performance, durable, economical, and environmentally sustainable solar desalination. Instead, the most promising future direction lies in the development of multifunctional hybrid coatings that integrate efficient photothermal conversion with strong mechanical stability, corrosion resistance, anti-fouling capability, scalable fabrication, and sustainable material selection. This integrated approach is expected to accelerate the transition of absorber coating technologies from laboratory-scale research to reliable, commercially deployable solar desalination systems.

5.2 Remaining Research Gaps

Despite remarkable progress in developing advanced absorber coatings for passive solar stills, this review shows that significant scientific and technological challenges remain before these materials can be widely adopted in commercial desalination systems. Although numerous coating technologies have shown promising improvements in photothermal conversion and freshwater productivity, their practical implementation is often constrained by the absence of standardized testing protocols, limited long-term durability data, insufficient techno-economic evaluation, and inadequate environmental life-cycle assessment. Furthermore, inconsistencies in experimental methodologies hinder direct comparison among published studies, making it difficult to identify the most suitable absorber materials for large-scale applications. Addressing these unresolved issues will require coordinated research efforts that integrate materials engineering, durability assessment, economic analysis, environmental sustainability, and system-level optimization. Therefore, the following section critically examines the principal research gaps that must be addressed to accelerate the transition of absorber coating technologies from laboratory-scale investigations to reliable, commercially viable, and sustainable solar desalination systems.

5.3 Future Research Roadmap

The critical assessment presented in this review indicates that the next generation of absorber coatings could be developed through an integrated research strategy that combines advances in materials science, thermal engineering, environmental sustainability, and system optimization. Future investigations could move beyond incremental improvements in photothermal efficiency and focus on designing absorber technologies capable of delivering reliable, economically viable, and environmentally sustainable freshwater production under real operating conditions. A coordinated research roadmap is therefore essential to accelerate the transition of promising laboratory-scale materials into commercially deployable solar desalination systems.

5.3.1 Development of Multifunctional Hybrid Coatings

One of the most promising research directions is developing multifunctional hybrid absorber coatings that combine the complementary advantages of different material classes. Carbon-based nanomaterials provide excellent solar absorption and rapid photothermal conversion, whereas metal oxides contribute chemical stability, corrosion resistance, and self-cleaning functionality. Similarly, porous carbon structures can improve thermal localization while bio-derived materials enhance sustainability and reduce production costs.

Future coating architectures could therefore integrate multiple functional properties within a single system rather than optimizing optical absorptivity alone. Hybrid coatings capable of simultaneously providing broadband solar absorption, efficient heat localization, strong substrate adhesion, anti-corrosion behavior, salt rejection, and long-term mechanical stability are expected to offer significantly greater practical value than single-component materials.

5.3.2 Green and Scalable Manufacturing Technologies

Although numerous advanced coating materials have demonstrated excellent laboratory performance, many rely on fabrication techniques that are difficult to scale for industrial production. Vacuum deposition, chemical vapor deposition, and sophisticated nanomaterial synthesis often require high energy consumption and specialized equipment, increasing manufacturing costs.

Future research should therefore prioritize environmentally benign fabrication methods that are compatible with large-scale production. Low-temperature synthesis routes, water-based coating formulations, spray deposition, roll-to-roll processing, and printable photothermal coatings represent attractive alternatives because they reduce manufacturing complexity while maintaining acceptable performance. Incorporating renewable raw materials and minimizing hazardous chemical usage will further improve the sustainability of absorber coating production.

5.3.3 Standardized Performance and Durability Evaluation

The review highlights the urgent need for harmonized testing procedures capable of generating reproducible and comparable performance data. Future experimental investigations could adopt standardized protocols that specify operating conditions, solar irradiance, basin geometry, water depth, salinity, coating thickness, and testing duration. Such standardization would enable objective comparison among different coating technologies and improve confidence in reported productivity enhancements.

Similarly, durability assessment should become an integral component of coating development. Accelerated aging tests incorporating ultraviolet exposure, thermal cycling, salt crystallization, corrosion, humidity variation, and mechanical abrasion should complement conventional thermal performance evaluation. Establishing internationally recognized durability standards would facilitate qualifying absorber coatings for commercial applications.

5.3.4 Digital Design and Artificial Intelligence

The rapid development of computational modeling and artificial intelligence offers new opportunities for accelerating absorber coating design. Machine learning algorithms can identify relationships between material composition, microstructure, and photothermal performance using large experimental datasets, thereby reducing the time required for material screening and optimization.

Computational fluid dynamics (CFD), finite element analysis, and multiphysics simulations can further improve understanding of heat transfer, fluid flow, and evaporation within coated solar stills. Coupling experimental investigations with data-driven optimization and computational modeling will enable more efficient design of absorber materials and system configurations while reducing experimental costs.

5.3.5 Integration with Advanced Solar Still Configurations

Future research could also investigate the interaction between absorber coatings and advanced solar still designs. Most current studies evaluate coatings using conventional basin-type systems, whereas relatively limited attention has been devoted to stepped, tubular, hemispherical, multi-effect, inclined wick, floating evaporator, and hybrid photovoltaic–thermal desalination systems.

Optimizing coating materials and system geometry together may produce synergistic improvements in freshwater productivity that exceed those achievable through material modification alone. Comparative studies evaluating identical coating materials across multiple solar still configurations would provide valuable guidance for practical system design.

5.3.6 Sustainability and Circular Economy

Environmental sustainability should remain a central consideration in future absorber development. Future work could focus on renewable carbon sources, agricultural residues, recycled industrial by-products, and biodegradable binder systems to reduce dependence on energy-intensive raw materials. At the same time, comprehensive life-cycle assessments could accompany new material development to quantify embodied energy, greenhouse gas emissions, resource consumption, recyclability, and end-of-life impacts.

Future investigations could also evaluate the environmental safety of nanostructured coatings by examining nanoparticle release, degradation products, and potential ecological impacts during long-term operation. Integrating sustainability assessment with material design will help ensure that improvements in desalination efficiency are achieved without creating new environmental challenges.

5.3.7 Pilot-scale Demonstration and Commercial Translation

A major challenge identified throughout this review is the gap between laboratory-scale demonstrations and practical implementation. Most published investigations evaluate absorber coatings under controlled experimental conditions using relatively small solar stills, providing limited information regarding long-term field performance.

Future research could therefore prioritize pilot-scale demonstrations under diverse climatic conditions using natural saline water. These studies could include continuous performance monitoring, maintenance evaluation, durability assessment, and comprehensive techno-economic analysis over extended operating periods. Collaboration among universities, research institutes, coating manufacturers, and water technology industries will be essential for translating promising laboratory materials into commercially viable solar desalination technologies.

5.3.8 Strategic Outlook

A systems-level approach could guide the future development of absorber coatings by simultaneously optimizing material performance, manufacturing feasibility, durability, environmental sustainability, and economic competitiveness. Rather than pursuing further increases in solar absorptivity, future research could prioritize multifunctional materials that maintain stable performance throughout their operational lifetime while remaining affordable and scalable for widespread implementation.

The roadmap proposed in this review suggests that the greatest advances are likely to emerge from interdisciplinary research integrating advanced materials engineering, computational optimization, standardized durability evaluation, life-cycle assessment, and pilot-scale validation. This approach will help transition absorber coating technologies from proof-of-concept studies to reliable components of next-generation solar desalination systems capable of addressing global freshwater challenges.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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