Asian Journal of Mechanical Engineering
ISSN: 2249-6289 (P); 3049-1886 (E)
Vol.14 No.1, 2025, pp.32-38

www.crijournals.org
DOI: https://doi.org/10.70112/arme-2025.14.1.4290

Sustainable Space Cooling through a Solar-Assisted Evaporative System with Porous Pads and Nanofluids

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(Received 5 March 2025; Revised 21 March 2025; Accepted 14 April 2025; Available online 17 April 2025)

Abstract - **The increasing global energy demand for cooling-driven by population growth and climate change-necessitates the urgent development of sustainable and energy-efficient alternatives to conventional vapor compression refrigeration systems. Evaporative cooling systems (ECSs) offer a viable solution due to their cost-effectiveness, environmental benefits, and low energy consumption. This review explores the fundamental principles, classifications, and advancements in evaporative cooling technology, with a particular focus on innovations in cooling pad materials and the application of nanofluids to enhance system performance. Traditional direct evaporative cooling (DEC) is effective in hot and dry climates but increases humidity levels, while indirect evaporative cooling (IEC) reduces temperature without adding moisture, though it typically exhibits lower effectiveness. Hybrid systems, such as indirect-direct evaporative cooling (IDEC), combine the advantages of both methods, offering superior cooling performance, often below the wet-bulb temperature. This review also highlights the integration of solar energy to power ECSs, further enhancing their sustainability. A critical component of ECS performance is the evaporative cooling pad. Recent research has investigated natural fibers and porous materials, such as terracotta and porous concrete, as sustainable and efficient alternatives to conventional pads. Furthermore, the introduction of nanofluids (e.g., copper oxide and aluminium oxide) as working fluids in heat exchangers has been shown to significantly improve heat transfer characteristics, thereby enhancing cooling capacity and overall system efficiency. This review synthesizes findings from recent literature to support the feasibility and potential of a novel experimental setup: a combined direct and indirect evaporative cooling system with strategically repositioned modules, utilizing porous terracotta bricks for direct cooling and a copper heat exchanger circulating nanofluid for indirect cooling. This innovative design aims to provide highly sustainable and efficient space cooling while addressing the limitations of existing technologies.**
Keywords: **Evaporative Cooling Systems (ECSS), Direct and Indirect Evaporative Cooling (DEC, IEC, IDEC), Cooling Pad Materials, Nanofluids, Sustainable Cooling Technologies**

I. INTRODUCTION

The accelerating global energy demand-projected to increase by 50% between 2005 and 2030-is primarily driven by reliance on fossil fuels, which significantly contribute to greenhouse gas emissions and global warming [1]. A substantial portion of this energy is consumed by air conditioning and refrigeration systems, particularly conventional vapor compression systems (VCSs), which are energy-intensive and utilize refrigerants that contribute to ozone depletion [5]. Consequently, there is an urgent need for sustainable, energy-efficient, and environmentally friendly cooling solutions to mitigate climate change and enhance energy security [2].

Evaporative cooling systems (ECSs) offer a viable alternative due to their low energy consumption, cost-effectiveness, and environmental benefits. ECSs leverage the natural phenomenon of water evaporation to produce a cooling effect, making them inherently simpler, more efficient, and more economical than compressor-based systems [6]. These systems are particularly effective in hot and dry climates, although advancements-such as multi-stage and hybrid configurations-are expanding their applicability to more humid regions. The coefficient of performance (COP) of ECSs can be remarkably high, reportedly ranging from 15 to 20, significantly outperforming traditional refrigeration methods.

This section provides a comprehensive overview of evaporative cooling technology, detailing its working principles, various types, and recent innovations that have improved performance and broadened applications. It also highlights the integration of sustainable materials and advanced heat transfer fluids, such as nanofluids, thereby setting the stage for evaluating the potential of a novel solar-assisted evaporative cooling system incorporating porous pads and nanofluids.

A. Principles of Evaporative Cooling

Evaporative cooling is fundamentally an adiabatic process, meaning the enthalpy of the air remains constant during cooling. It is based on the principle of latent heat of vaporization: when water evaporates into an airstream, it absorbs sensible heat from the surrounding air, thereby lowering the air temperature while simultaneously increasing humidity. The effectiveness of this process is limited by the air's wet-bulb temperature, as direct evaporative cooling cannot reduce air temperature below this point [1].

The core mechanism involves simultaneous heat and mass transfer between air and water [4]. When unsaturated air contacts a wet surface, water molecules evaporate into the air [5]. The energy required for this phase change is drawn from the sensible heat of the air, resulting in a temperature drop [6]. The driving force for evaporation is the vapor pressure difference between the water surface and the surrounding air [3]. The efficiency of this heat and mass transfer process is influenced by several factors, including the contact surface area, airflow rate, and the physical properties of the wetted material [1].

1. Types of Evaporative Cooling Systems

Evaporative cooling systems are broadly classified into three main categories, each with distinct operational characteristics and applications [1].

a. Direct Evaporative Cooling Systems (DECS)

In DECS, the airstream to be cooled comes into direct contact with wetted evaporative media or water droplets [3]. As water evaporates, the air temperature decreases and its humidity increases. This system is simple in design, cost-effective, and consumes significantly less power compared to conventional refrigeration systems. DECS are most suitable for hot and dry climates where the ambient air has low relative humidity. Common applications include residential cooling and short-term preservation of agricultural products and fruits. However, the primary limitation of DECS is the increase in humidity, which can cause discomfort in moist environments and may lead to corrosion of metallic components or warping of materials. The wet-bulb effectiveness of DECS typically ranges from 70% to 95% [1].

b. Indirect Evaporative Cooling Systems (IECS)

Unlike DECS, IECS cool the air without increasing its humidity. This is achieved by separating the primary (supply) airstream from the secondary (working) airstream that undergoes evaporation. A heat exchanger transfers heat from the primary air to the wetted secondary air, which then exhausts the absorbed moisture [3]. This arrangement enables sensible cooling without humidity addition, making IECS suitable for a wider range of climates, including those with higher ambient humidity. While IECS provide the advantage of humidity control, their effectiveness is generally lower than that of DECS due to the additional heat transfer step [1].

B. Multistage Evaporative Cooling Systems

To overcome the limitations of single-stage systems and achieve better performance across diverse climatic conditions, multistage ECSs combine direct and indirect cooling principles.

1. Two-Stage Indirect-Direct Evaporative Cooling Systems (IDECS)

In this configuration, an IECS typically precedes a DECS. The indirect stage first sensibly cools the outdoor air without humidification, and this pre-cooled air then enters the direct stage for further cooling and humidification. This arrangement can achieve air temperatures below the wet-bulb temperature, with reported effectiveness ranging from 90% to 115%. However, IDECS involve more complex designs and higher initial costs [1].

2. Three-Stage and Hybrid Systems

More advanced multistage systems may incorporate additional cooling stages or integrate with other technologies, such as solid desiccant dehumidification or vapor compression systems [3]. These hybrid systems can provide significant energy savings (54%-82% compared to conventional cooling) and improved humidity control. For example, integrating ECSs with solid desiccant dehumidification systems can further enhance thermal comfort, particularly in hot and humid climates [1].

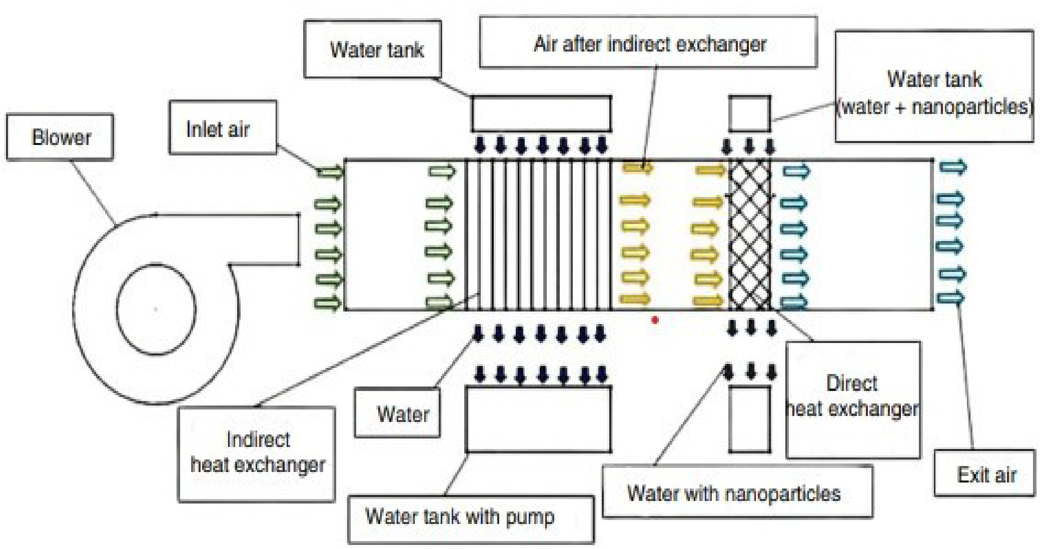

Fig.1 Schematic Representation of an Indirect-Direct Evaporative Cooler [10]

C. Innovations and Performance Enhancements

Recent innovations in ECSs have focused on improving efficiency, reducing costs, and expanding applicability. These advancements involve material science, design optimization, and integration with renewable energy sources.

1. Cooling Pad Materials

The evaporative media, or cooling pads, are critical components influencing system performance, including pressure drop, air-water contact surface area, and maintenance [1]. Conventional cellulose pads have been widely used; however, research is increasingly focused on sustainable and locally available natural fibers such as coconut coir, palm fiber, rice husk, straw, jute, and natural fiber-based composites [7]. These alternatives provide advantages such as reduced initial cost, biodegradability, and a lower carbon footprint [1]. Porous materials, including terracotta bricks and porous concrete, are also being investigated due to their excellent water absorption, heat transfer, and self-cooling capabilities [5]. The proposed project employs terracotta bricks, aligning with these innovations.

2. Nanofluids for Enhanced Heat Transfer

A major innovation in cooling systems is the application of nanofluids-suspensions of nanometer-sized particles in a base fluid [4]. Nanofluids exhibit superior thermophysical properties, including enhanced thermal conductivity and optical characteristics (higher absorption and lower emittance), compared to conventional fluids such as water. These properties make them highly effective heat transfer fluids, capable of improving the performance of heat exchangers in indirect evaporative cooling systems. Studies have demonstrated that nanofluids such as Al_2O_3, CuO, and TiO_2 can significantly increase heat transfer coefficients and overall system efficiency, resulting in higher cooling capacity and reduced energy consumption [6]. The proposed project applies copper oxide and aluminum oxide nanofluids in the indirect system's copper heat exchanger as a direct implementation of this approach.

3. Design Modifications and Integration

Performance enhancements can also be achieved through optimized system designs, including the use of heat pipes for passive heat transfer, finned heat exchangers [1], and surface alterations in heat exchanger channels (e.g., capsule-embossed, finned, or corrugated) to improve heat and mass transfer [2]. The integration of evaporative cooling with vapor compression systems for condenser cooling or with desiccant dehumidification further increases system COP and reduces energy consumption [1].

D. Project Overview and Innovations

The proposed experimental setup represents a novel combination of these advancements, targeting sustainable space cooling. The project integrates a direct evaporative cooling system with terracotta porous pads and an indirect evaporative cooling system utilizing a copper heat exchanger with nanofluids (copper oxide, aluminum oxide). A unique feature of the design is the planned experimentation with the direct and indirect systems positioned interchangeably, enabling a comprehensive performance evaluation.

The setup consists of a 2 × 2 × 5 ft duct, with three sides made of CRC sheet metal for structural integrity and one side of acrylic sheet for visual observation. Temperature and humidity sensors are strategically placed before the direct system, after the direct system, and after the indirect system to monitor the thermodynamic states of the air. Additional temperature sensors are installed at the water inlets and outlets of both systems. An inlet duct fan draws ambient air into the system. The direct system employs terracotta bricks, continuously wetted by a sprinkler, leveraging their natural porosity for efficient humidification and cooling. The indirect system features a copper heat exchanger through which a mixture of water and nanofluids (copper oxide, aluminum oxide) circulates, providing sensible cooling. This combined approach aims to harness the high effectiveness of direct cooling in the initial stage and the humidity-independent sensible cooling of the indirect stage, enhanced by the superior heat transfer properties of nanofluids. The experimental investigation will yield critical data on temperature reduction, humidity control, and overall system efficiency, contributing to the development of highly sustainable cooling solutions.

II. LITERATURE REVIEW

Kapilan *et al.* [1] ["A Comprehensive Review on Evaporative Cooling Systems"] examined various types and developments of ECSs, emphasizing their energy efficiency, cost-effectiveness, and environmental benefits compared to vapor compression refrigeration. The study classified ECSs into direct, indirect, and multi-stage systems, and highlighted the role of natural fiber-based cooling pads and solar power integration in reducing cost and energy dependence. It also reviewed innovations such as heat pipes and hybrid ECS models aimed at improving performance. Direct evaporative cooling (DEC) was presented as highly efficient for hot and dry climates, achieving wet-bulb effectiveness between 70%-95%. While limitations in humid conditions were noted, ECSs were endorsed for applications such as fruit and vegetable storage, poultry, and greenhouse cooling. The study stressed the use of natural materials (e.g., coconut coir, jute, wood fiber) for their cost and environmental benefits. Enhancement techniques, including water spray systems, honeycomb pads, and solar-powered operations, were also discussed. The review concluded that ECSs, particularly when enhanced with multistage design and alternative pad materials, represent viable, sustainable alternatives to conventional cooling systems, and called for further research into component optimization and operating conditions.

Kashyap *et al.* [2] [*"*Performance Enhancement of Regenerative Evaporative Cooler by Surface Alterations and Using Ternary Hybrid Nanofluids"] investigated regenerative evaporative coolers enhanced by surface profile alterations and ternary hybrid nanofluids (a combination of three nanoparticles suspended in water). Simulation analysis was used to evaluate four surface configurations-flat, finned, corrugated, and capsule-embossed plates-together with six nanoparticle combinations. Findings revealed that surface geometry modification had a greater effect on performance than nanofluid addition alone.

The capsule-embossed plate yielded the highest improvements in COP, exergy efficiency, and sustainability index. The best-performing configuration reduced dew-point temperature and increased dew-point effectiveness while maintaining structural and thermal efficiency. Nanofluids alone produced modest improvements, but when combined with surface modifications, significant performance enhancements were observed. Economic and environmental assessments concluded that while operational costs slightly increased, the benefits of reduced energy use and emissions outweighed the drawbacks.

Colangelo *et al. [4]* [*"*Assessment of a Desiccant Cooling System in a Traditional and Innovative Nanofluid HVAC System"] presented a comparative simulation-based analysis of a desiccant cooling system integrated with nanofluids versus a traditional HVAC system in a university building. Using TRNSYS software, four cases were simulated: conventional HVAC with water-glycol, HVAC with nanofluids, desiccant cooling with water-glycol, and desiccant cooling with nanofluids. Results showed that desiccant cooling outperformed conventional HVAC, particularly under summer conditions, due to reduced humidity load and improved latent heat handling. Nanofluids enhanced thermal conductivity and heat transfer rates, improving performance by 21% compared to water-glycol systems. Desiccant cooling also reduced energy consumption and carbon footprint, supporting its use in sustainable cooling strategies. The study concluded that integrating nanofluids into desiccant systems produces synergistic effects that boost efficiency while maintaining eco-friendly performance.

Yang *et al.* [3] [*"*Developments in Evaporative Cooling and Enhanced Evaporative Cooling - A Review"] provided a detailed review of traditional and enhanced evaporative cooling systems. The paper classified ECSs into air-mediated and water-mediated, as well as direct and indirect types. Enhanced systems included membranes, desiccants, and hybrid setups, which improve efficiency beyond standard configurations. Applications reviewed included HVAC, microclimate cooling (e.g., wearable cooling garments), and industrial process cooling. Enhanced evaporative cooling technologies such as membrane-based and desiccant-assisted cooling were shown to improve effectiveness and indoor air quality. The paper highlighted the importance of compact designs and energy-efficient components for broader climate adaptability and reduced greenhouse gas emissions. The authors concluded that enhanced ECS technologies hold significant potential for sustainable cooling and recommended further research into material innovation and hybridization strategies.

Elsheikh *et al.* [6] [*"*Applications of Nanofluids in Solar Energy: A Review of Recent Advances"] reviewed nanofluid applications in solar energy systems (SESs), including solar collectors, photovoltaic/thermal (PV/T) systems, solar water heaters, and desalination units. The review emphasized advantages such as superior thermal conductivity, higher solar absorption, reduced surface fouling, and increased heat transfer rates. Nanoparticles such as Al_2O_3, CuO, TiO_2, and CNTs were assessed for their suitability in direct absorption solar collectors and hybrid systems.

Reported results indicated efficiency improvements of up to 10%-30% in solar collectors and up to 5% in PV/T systems, due to enhanced optical and thermal properties. The study also reviewed modeling approaches for predicting nanofluid behavior, while identifying challenges including stability, sedimentation, and cost. The authors concluded that nanofluids are promising for improving the performance of SESs while reducing greenhouse gas emissions and energy consumption. However, they emphasized the need for long-term field trials, standardized preparation methods, and cost-benefit analyses to ensure practical feasibility in large-scale applications.

Rahman *et al.* [5] *"*Experimental Investigation of a Novel Evaporative Cooling Pad Made of Cement-Free Porous Concrete," investigated the performance of a new type of evaporative cooling pad (ECP) made from cement-free porous concrete as an eco-friendly and sustainable alternative for greenhouse cooling in arid climates. The study employed a wind tunnel experiment, where porous concrete pads were tested under different inlet air temperatures while maintaining a constant airflow velocity of 2.5 m/s.

The novel ECP demonstrated an average cooling effectiveness of 0.97, with some trials exceeding 100% effectiveness due to the self-cooling properties of porous concrete. The heat transfer coefficient reached 10.17 $kW/m^2°C$, and the system achieved a sensible cooling capacity of -11.46 W. Furthermore, a high mass transfer coefficient (1.56 m/s) and mass transfer rate (5.84 g/s) confirmed the material's excellent moisture-handling capability. Compared to conventional materials such as cellulose and jute, the porous concrete ECP outperformed in both durability and thermal performance, while remaining environmentally sustainable due to its cement-free composition.

The study concluded that this innovative material could serve dual purposes as both a structural element and an efficient cooling pad in greenhouses, especially in hot and dry environments, and suggested further research into its long-term mechanical performance and scalability.

Abada *et al.* [7], "Performance Evaluation of Fabrics for Evaporative Cooling Applications," examined the suitability of various textile fabrics as alternative wet mediums for indirect evaporative cooling (IEC) systems. The study assessed key properties such as capillary wicking, diffusivity, evaporation capacity, and moisture retention of woven fabrics compared to traditional Kraft paper.

A novel testing setup was designed to measure the vertical wicking ability of textiles to simulate their behavior under real cooling system conditions. The experimental results revealed that many textile fabrics demonstrated superior performance over Kraft paper, with some fabrics exhibiting 160% to 355% higher absorbency. The weave type and compactness of the fabric were found to significantly enhance moisture retention and capillary action, resulting in more efficient evaporation and better thermal exchange. Additionally, fabrics offered advantages in durability, flexibility, and environmental sustainability.

The study concluded that selecting fabrics with optimal hydrophilic properties can greatly improve the effectiveness of IEC systems, reduce water usage, and extend system lifespan. Two specific fabric types were highlighted as the most suitable for further development due to their combined mechanical strength and thermal performance. The authors recommended further research on fabric-based cooling elements to optimize IEC designs and reduce reliance on conventional synthetic or paper-based substrates.

Alktranee and Bencs [8], "Experimental Comparative Study on Using Different Cooling Techniques with Photovoltaic Modules," presented an experimental comparison of multiple passive and active cooling strategies for photovoltaic (PV) modules to enhance energy efficiency in high-temperature environments. The study investigated methods including air cooling, water spray, phase change materials (PCMs), and evaporative cooling systems. Each technique was evaluated based on its impact on PV surface temperature, electrical efficiency, and overall energy yield.

Results showed that evaporative cooling consistently delivered the highest performance enhancement, reducing surface temperature by up to 18 °C and improving efficiency by approximately 15% compared to uncooled modules. PCM-based systems also showed promising performance due to their thermal storage capability, particularly during fluctuating weather conditions. However, they were less effective than evaporative techniques during peak solar radiation. Air cooling and water spraying, though simpler and less costly, offered moderate improvements. The authors concluded that hybrid systems combining PCM and evaporative techniques may offer a practical balance of efficiency, cost, and feasibility. The paper recommended further development of integrated cooling systems tailored to local climatic conditions and suggested optimizing thermal contact, pad design, and water delivery mechanisms for improved outcomes in future PV applications.

Kumar and Sharma [9], "Experimental Thermal Analysis of Eco-Friendly, Sustainable and Biodegradable New Mud/Clay-Based Cooling Pad for Evaporative Coolers," explored the thermal performance of a newly designed mud/clay-based evaporative cooling pad aimed at enhancing cooling efficiency for desert coolers in arid and semi-arid regions. The cooling pad consisted of *mitti* (clay) balls arranged in layers with inline or staggered formation, creating a porous structure that maximized the surface area for evaporation.

The experimental setup included a test rig simulating varying air velocities (4.3-7.3 m/s), water flow rates, and inlet air temperatures (up to 42 °C). Results indicated a maximum temperature drop of 17 °C and a peak humidifying efficiency of 86%, making it competitive with traditional cellulose and jute pads. The mud/clay pad also showed strong durability and water retention properties while being biodegradable, low-cost, and accessible to lower-income populations. Its modular design allowed for easy replacement and customization.

The study highlighted the ecological and economic benefits of this design, advocating its use in rural and off-grid applications. The authors concluded that the mud/clay ball pad is a promising alternative to synthetic cooling media, offering both high thermal performance and sustainability. They further recommended optimizing geometry, packing density, and integration with solar-powered fan systems for commercialization.

Ganesha *et al.* [10], "Performance Evaluation of an Indirect-Direct Evaporative Cooler Using Aluminum Oxide-Based Nanofluid," presented an experimental study aimed at improving the efficiency of evaporative cooling systems by integrating aluminum oxide (Al_2O_3) nanoparticles in the indirect cooling stage. The system comprised a cross-flow heat exchanger for the indirect stage, where nanofluid cooled air sensibly, followed by a direct evaporative cooler using Celdek 7090 pads.

The authors varied air velocity (3-6 m/s), water flow rate (1-4 LPM), and nanoparticle concentration (0-2.5%) to assess cooling performance. Results showed that incorporating 1% Al_2O_3 nanoparticles increased cooling efficiency and significantly reduced the exit air temperature and relative humidity-achieving a 39.2% higher ΔDBT and 27% lower ΔRH compared to direct evaporative cooling alone.

Optimal conditions were observed at a water flow rate of 3 LPM and air velocity of 5 m/s, yielding a maximum cooling efficiency of 96% and a COP of 5.9. Beyond 1% nanoparticle concentration, performance declined due to increased fluid viscosity and nanoparticle agglomeration. Compared to conventional and other hybrid systems, the proposed setup demonstrated superior thermal performance.

TABLE I

Sl. No.	Author	Year	Focus of Paper	Key Points in Coverage	Techniques Used	Parameters Used	Outcome	Conclusion
1	Kapilan *et al.,*	2023	Review of Evaporative Cooling Systems	Types of ECS (Direct, Indirect, Multi-Stage); Natural Fibers; Solar Applications; Agriculture and Greenhouse Applications	Literature review	Wet-Bulb Effectiveness, Pad Materials, and COP	DEC effective in hot-dry climates with 70-95% wet-bulb effectiveness	ECS can replace traditional systems through multistage designs and natural materials
2	Kashyap *et al.,*	2021	Performance Enhancement Using Hybrid Nanofluids and Surfaces	Ternary Nanofluids; Flat, Finned, Corrugated, and Capsule-Embossed Plates	Simulation	COP, Exergy Efficiency, and Dew Point Temperature	Capsule-embossed plate showed best performance; surface geometry more influential than nanofluids alone	Hybrid nanofluid with surface profiling is most effective,particularly in hot-dry regions
3	Colangelo *et al.,*	2022	HVAC Versus Desiccant System Simulation Using Nanofluids	HVAC With and Without Nanofluids Versus Desiccant Systems Under Identical Building Loads	TRNSYS simulation	Energy Use, Cooling Load, and Carbon Footprint	Desiccant system combined with nanofluids improved performance by 21%	Nanofluid-enhanced desiccant cooling shows strong potential in humid climates
4	Yang *et al.,*	2019	Review of Enhanced Evaporative Cooling Technologies	Enhanced ECS: Desiccants, Membranes, and Hybrids for HVAC and Microclimate Cooling	Review	Energy Savings, Emissions, and Cooling Effectiveness	Enhanced ECS provided better cooling and reduced emissions	Further research and development on materials and hybrid cooling methods is recommended
5	Elsheikh *et al.,*	2018	Nanofluids in Solar Energy Systems	Nanofluids in Solar Collectors, PV/T Systems, Heaters, and Desalination	Review	Thermal Conductivity, Absorption, and Stability	Efficiency gains of 10-30% in collectors and ~5% in PV/T systems	Nanofluids are promising stability, preparation, and cost analysis are required
6	Rahman *et al.,*	2022	Cement-Free Porous Concrete for Cooling Pads	Wind Tunnel Testing of Concrete ECPs for Greenhouse Cooling	Experimental	Cooling Effectiveness, Heat and Mass Transfer	Average effectiveness of 0.97, exceeding 100% in some cases; heat transfer rate of 10.17 kW/m²·°C	ECS is a strong candidate for eco-friendly cooling in greenhouse applications
7	Abada *et al.,*	2022	Fabric Materials in IEC Systems	Textiles Versus Kraft Paper: Wicking, Moisture Retention, and Evaporation Capacity	Experimental	Wicking, Retention, and Evaporation Rate	Some fabrics were 160-355% more absorbent than Kraft paper, demonstrating better overall performance	Fabric pads can outperform paper; further investigation is recommended
8	Alktranee & Bencs	2023	Cooling of Photovoltaic Panels Using Multiple Method	Comparative Study of Air, Water Spray, PCM, and ECS Cooling for PV Panels	Experimental	PV Temperature and Electrical Efficiency	ECS reduced PV temperature by 18 °C and improved efficiency by ~15%	Hybrid PCM with ECS is promising for photovoltaic applications
9	Kumar & Sharma	2024	Mud/Clay-Based ECPs for Desert Coolers	Mud Ball Pads in Inline and Staggered Layers: Testing Under Variable Airflow and	Experimental	Temperature Drop and Humidifying Efficiency	Maximum temperature drop of 17 °C with 86%	Low-cost and sustainable; suitable for rural and off-

				Water Flow Conditions			humidifying efficiency; materials were durable and biodegradable	grid cooling systems
10	Ganesha *et al.,*	2023	Indirect-Direct ECS Using Al_2O_3 Nanofluid	Cross-Flow Heat Exchanger with Nanofluid in Indirect Stage and Celdek Pad in Direct Stage	Experimental	COP, ΔDBT, RH, and Flow Rate	Cooling efficiency of 96% with COP of 5.9, outperforming conventional systems and standalone DEC	Nanofluid-enhanced ID-ECS demonstrates good performance but requires optimization of concentration and flow parameters

III. CONCLUSION

The increasing global energy crisis and growing environmental concerns necessitate a paradigm shift toward sustainable and energy-efficient cooling solutions. Evaporative cooling systems (ECSs) have emerged as a promising alternative to conventional vapor compression refrigeration, offering advantages in energy consumption, cost, and environmental impact. This review highlights the critical role of advancements in ECSs, particularly through innovations in cooling pad materials and the integration of nanofluids. Literature consistently demonstrates that multistage evaporative cooling systems, combining direct and indirect approaches, can achieve superior performance, including temperatures below the wet-bulb limit, thereby extending applicability. Innovations in cooling pad materials-transitioning from conventional cellulose to sustainable natural fibers such as terracotta, porous concrete, and various fabrics-offer reduced cost, lower environmental footprint, and comparable or enhanced performance. Furthermore, the application of nanofluids presents a transformative opportunity to significantly enhance heat transfer rates in indirect cooling heat exchangers, thereby increasing system efficiency and cooling capacity. The proposed experimental setup, featuring a direct evaporative system with porous terracotta pads and an indirect system utilizing a copper heat exchanger with nanofluids (copper oxide, aluminum oxide), addresses these innovative pathways. By strategically reconfiguring the placement of direct and indirect stages, the design aims to optimize the combined cooling effect. A comprehensive sensor array will provide detailed thermodynamic data, enabling rigorous evaluation of the system's capability to deliver sustainable space cooling. This synthesis of established principles with advanced materials and fluid technologies represents a significant step toward developing highly efficient, environmentally responsible, and economically viable cooling solutions for future energy demands.

Declaration of Conflicting Interests
The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The authors received no financial support for the research, authorship, and/or publication of this article.

Use of Artificial Intelligence (AI)-Assisted Technology for Manuscript Preparation
The authors confirm that no AI-assisted technologies were used in the preparation or writing of the manuscript, and no images were altered using AI.

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