ISSN : 2455-9679
SJIF Impact Factor : 6.190

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IJRTSM

INTERNATIONAL JOURNAL OF RECENT TECHNOLOGY SCIENCE & MANAGEMENT

"DESIGN AND DEVELOPMENT APPROACHES FOR IMPROVING PRODUCTIVITY OF TUBULAR SOLAR STILLS: A REVIEW"

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ABSTRACT

Freshwater scarcity has become a critical global concern due to population growth, industrialization, climate change, groundwater depletion, and increasing contamination of available water resources. Solar desalination is one of the most sustainable and low-cost approaches for producing potable water from saline, brackish, or contaminated water, particularly in remote, arid, coastal, and off-grid regions. Among different solar still configurations, tubular solar stills have gained considerable research attention because of their curved transparent cover, compact structure, larger condensation surface, better solar radiation acceptance, and suitability for modular installation. However, the productivity of a conventional tubular solar still remains limited due to low evaporation rate, high thermal losses, poor condensation control, salt deposition, and limited night-time operation. Therefore, several design and development approaches have been proposed to improve freshwater yield and thermal performance. This review paper discusses major productivity enhancement techniques for tubular solar stills, including water-depth optimization, absorber surface modification using graphene-based nano-coatings, fins and extended surfaces, wick materials, phase change materials, nanoparticles and nanofluids (with particular emphasis on graphene and carbon-based nanomaterials), reflectors, concentrators, cover cooling, external condensers, and hybrid integration with solar collectors or photovoltaic-thermal systems. The incorporation of graphene materials significantly enhances solar absorptivity, thermal conductivity, and heat transfer characteristics, leading to improved evaporation rates and overall system efficiency. The review indicates that no single modification can fully overcome the productivity limitation of tubular solar stills; instead, integrated designs combining evaporation enhancement, thermal storage, solar radiation concentration, condensation improvement, and advanced graphene-based material applications provide better performance. Passive modifications such as shallow water depth, graphene-coated absorber surfaces, wick materials, and reflectors are suitable for low-cost rural applications, whereas hybrid systems using PCM, graphene nanofluids, external condensers, and evacuated tube collectors are more suitable for higher freshwater demand. The paper also identifies major research gaps related to long-term durability of graphene coatings, salt scaling, material degradation, economic feasibility, standard testing, and field validation. Overall, tubular solar stills have strong potential for sustainable decentralized freshwater production if productivity enhancement strategies are developed with equal attention to efficiency, cost, simplicity, and operational reliability.

Keywords: *Tubular solar still; solar desalination; freshwater productivity; graphene nanocoating; nanofluids; passive solar still; phase change material; wick material; thermal performance; condensation enhancement.*

I. INTRODUCTION

The increasing demand for potable water has become one of the most serious global challenges due to population growth, urbanization, industrial expansion, agricultural water consumption, climate change, and groundwater depletion. In many rural, coastal, island, desert, and semi-arid regions, freshwater resources are either insufficient or contaminated by dissolved salts, heavy metals, microorganisms, and other impurities. Although modern desalination technologies such as reverse osmosis, multi-stage flash distillation, multi-effect distillation, vapour compression, and electrodialysis are capable of producing large quantities of freshwater, these technologies usually require high capital investment, continuous electricity supply, skilled operation, chemical pretreatment, and regular maintenance [1], [2]. Therefore, such systems are not always suitable for small communities, remote settlements, emergency applications, or low-income regions. In this context, solar distillation has emerged as a simple, renewable, and environmentally friendly method for freshwater production using freely available solar energy.

Solar stills work on the natural hydrological principle of evaporation and condensation. Saline or brackish water is heated by solar radiation, water vapour is generated from the heated water surface, and the vapour condenses on a relatively cooler transparent cover to produce distilled water. The process removes salts, suspended particles, and many biological impurities, making it suitable for producing drinking water at small scale [3]. Conventional basin-type solar stills are simple in design and easy to fabricate, but their productivity is generally low because of limited evaporation area, high thermal losses, poor condensation rate, and restricted heat and mass transfer inside the still [4]. For this reason, many modified solar still designs have been proposed, including single-slope, double-slope, pyramid, hemispherical, stepped, inclined, wick, multi-effect, and tubular solar stills [5], [6].

Among these designs, the tubular solar still has received increasing research attention because of its compact geometry, curved transparent cover, large condensation surface, and improved solar radiation acceptance from different directions during the day. Unlike a conventional inclined glass solar still, the tubular still generally consists of a cylindrical or semi-cylindrical transparent cover placed above a blackened absorber basin. The curved cover acts simultaneously as the radiation-transmitting surface and condensation surface. This geometry increases the effective surface area available for condensation and allows solar radiation to enter over a wider angular range [7]. Tubular solar stills are also attractive because they can be developed as modular systems, connected in series or parallel, and installed in remote locations with relatively simple fabrication requirements.

However, the basic tubular solar still, still suffers from low freshwater yield when operated without enhancement techniques. The productivity of a solar still depends mainly on the temperature difference between the evaporating water surface and condensing cover. If the saline water temperature remains low, evaporation is limited. If the transparent cover temperature becomes too high, condensation becomes weak. Similarly, excessive water depth increases thermal inertia, poor absorber design reduces solar absorption, and weak internal vapour circulation restricts mass transfer [8], [9]. Therefore, the development of improved tubular solar stills requires integrated design approaches that enhance solar energy absorption, heat transfer, evaporation rate, vapour movement, condensation rate, and thermal storage.

The design and development of productivity-enhanced tubular solar stills has become an important research area because even small improvements in daily yield can significantly improve the practical usefulness of passive solar desalination systems. Researchers have investigated several modification strategies, including optimized water depth, absorber coating, finned absorber plates, corrugated surfaces, wick materials, phase change materials, nanoparticles, reflectors, concentrators, external condensers, cover cooling, evacuated tube collectors, photovoltaic-thermal integration, and hybrid energy input [10]–[13]. Each method improves productivity through a different physical mechanism. For example, wick materials increase evaporation surface area by forming a thin water film, phase change materials store heat for evening or night operation, nanoparticles increase thermal conductivity and solar absorption, and condenser cooling improves vapour condensation.

The present review paper discusses the design and development approaches used for improving the productivity of tubular solar stills. The review is organized into five main sections without internal subheadings. The first section introduces the need for solar desalination and highlights the importance of tubular solar stills. The second section explains the basic configuration, working principle, and performance limitations of tubular solar stills. The third section discusses major design and development approaches for productivity improvement. The fourth section provides a comparative discussion of enhancement methods and identifies research gaps. The fifth section presents the conclusion.

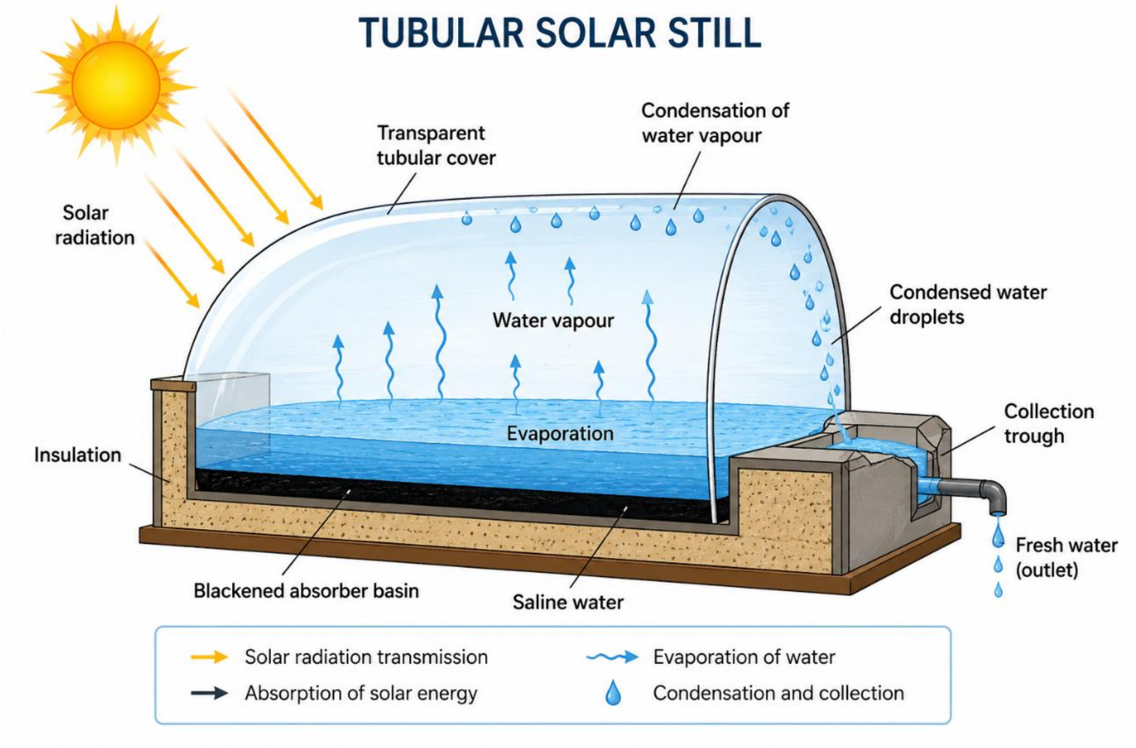

Fig. 1. Basic schematic representation of a tubular solar still showing solar radiation transmission, absorber heating, water evaporation, vapour condensation on the curved transparent cover, and freshwater collection.

II. TUBULAR SOLAR STILL TECHNOLOGY

2. Tubular Solar Still Configuration and Performance Limitations

A tubular solar still is generally composed of a transparent cylindrical or semi-cylindrical cover, blackened absorber basin, saline water layer, insulation, freshwater collection channel, and supporting frame. The transparent cover may be made of glass, acrylic, polycarbonate, or other transparent materials with good solar transmissivity. The absorber basin is usually coated black to increase solar absorption and is placed at the lower portion of the tubular enclosure. Saline or brackish water is supplied into the basin at a controlled depth. Solar radiation passes through the curved transparent cover and is absorbed by the blackened basin and saline water. As the water temperature increases, evaporation occurs from the water surface. The generated vapour moves upward and condenses on the inner surface of the transparent tube, which is relatively cooler due to heat loss to the ambient environment. The condensed droplets then flow along the curved inner wall and are collected through a trough or channel [14].

The performance of a tubular solar still is governed by several thermal and mass transfer processes. These include transmission of solar radiation through the cover, absorption of radiation by the basin, heat transfer from basin to water, convective and evaporative heat transfer from water to vapour, condensation heat transfer from vapour to cover, radiative exchange between water and cover, conductive heat loss through the basin, and convective heat loss from the cover to ambient air. The freshwater yield mainly depends on the evaporative heat transfer rate, which is controlled by water temperature, cover temperature, vapour pressure difference, internal humidity, and air-vapour circulation inside the still [15].

The curved geometry of the tubular still provides several advantages over conventional single-slope or double-slope basin stills. First, the cylindrical surface increases the condensation area because the inner surface of the tube is larger than a simple inclined glass cover of equivalent footprint. Second, the curved cover can receive solar radiation from different angles throughout the day, reducing the dependence on one fixed inclination angle. Third, the compact enclosed space reduces the distance between the evaporating water surface and condensing surface, which may support faster condensation. Fourth, the modular shape is suitable for scaling by connecting several tubular units. These features make the tubular solar still suitable for rural desalination, household water production, laboratory-scale purification, and emergency freshwater supply [16].

Despite these advantages, the conventional tubular solar still has several performance limitations. The first major limitation is low evaporation rate. In a basic design, the absorber surface area is limited, and the saline water layer may have high thermal mass. When water depth is high, a significant portion of absorbed solar energy is consumed in raising the bulk water temperature rather than producing vapour. As a result, the still may show delayed response during morning hours and reduced yield under fluctuating solar radiation. The second limitation is heat loss from the transparent cover and basin. Although cover cooling is necessary for condensation, excessive heat loss reduces the available energy for evaporation. Poor insulation at the bottom and sides also decreases thermal efficiency.

The third limitation is weak condensation control. A solar still requires both high water temperature and low condensing cover temperature. However, in many tubular designs, the transparent cover also receives direct solar radiation and becomes hot during peak sunshine hours. This reduces the temperature difference between vapour and cover, thereby lowering condensation rate. The fourth limitation is salt deposition and scaling. As water evaporates, salts remain in the basin and gradually increase the salinity of the remaining water. Salt crystals may deposit on the absorber surface, wick material, or internal components, reducing heat absorption and evaporation efficiency. Regular cleaning is therefore necessary.

The fifth limitation is poor night-time productivity. Conventional passive solar stills usually produce most of their water during daytime. After sunset, evaporation decreases rapidly because stored heat in the basin water is limited. Without thermal energy storage, night production remains low. The sixth limitation is material durability. Transparent polymeric tubes may degrade under ultraviolet radiation, high temperature, and saline conditions. Glass tubes offer better optical stability but are heavier and more fragile. The seventh limitation is the difficulty of achieving high productivity without increasing cost or complexity. Many enhancement techniques improve freshwater yield but also increase fabrication cost, maintenance requirements, or system weight [17].

Therefore, an effective tubular solar still design must balance productivity, cost, durability, simplicity, and maintenance. For practical application, the system should not only show high daily yield under laboratory conditions but also demonstrate reliable performance under real outdoor conditions. This requires careful selection of absorber material, water depth, transparent cover, insulation, evaporation enhancement method, condensation control strategy, and thermal storage arrangement.

III. DESIGN AND DEVELOPMENT APPROACHES FOR PRODUCTIVITY IMPROVEMENT

Several design and development approaches have been used to improve the productivity of tubular solar stills. These approaches aim to enhance one or more controlling mechanisms such as solar absorption, basin heat transfer, evaporation surface area, water-cover temperature difference, condensation rate, thermal storage, and internal vapour circulation. Since the productivity of a tubular solar still is a combined result of heat and mass transfer, the most effective improvement is often achieved by integrating multiple enhancement techniques rather than relying on a single modification.

One of the simplest approaches is the optimization of saline water depth. Lower water depth reduces thermal inertia and allows the water to reach higher temperature more quickly. This improves evaporation rate during sunshine hours. However, very low water depth may create operational problems such as dry zones, salt crust formation, and frequent refilling. Therefore, optimum water depth must be selected based on basin geometry, solar intensity, operating duration, and desired water output [18]. In tubular solar stills, thin water layers are particularly beneficial because the absorber area is generally elongated and narrow. Shallow water operation can be combined with continuous or intermittent feed-water control to maintain stable evaporation conditions.

Another important method is the modification of absorber plate geometry and surface characteristics. A blackened absorber is essential for increasing solar radiation absorption. However, ordinary black paint may degrade over time under saline and high-temperature conditions. Selective coatings, matte black surfaces, roughened surfaces, and corrosion-resistant coatings can improve solar absorption and long-term performance. Corrugated absorbers, stepped absorbers, V-shaped plates, and curved absorber trays increase effective heat transfer area and improve contact between water and heated surface. Corrugated and roughened surfaces also create local disturbances in the water layer, reducing thermal resistance and improving heat transfer from absorber to water [19].

Fins and extended surfaces are widely used to increase the heat transfer area between absorber and saline water. Aluminium, copper, or galvanized iron fins may be attached to the absorber plate to conduct heat into the water. Longitudinal fins, pin fins, rectangular fins, and circular fins have been investigated in different still configurations. In tubular solar stills, fin placement must be carefully designed so that fins improve heat transfer without obstructing vapour flow or increasing salt deposition. Fins can increase water temperature and enhance evaporation during daytime, but they may also increase material cost and cleaning difficulty. Therefore, fin geometry, spacing, height, and material must be optimized [20].

Wick materials are another effective approach for improving evaporation. A wick solar still uses porous or fibrous material to spread saline water into a thin film by capillary action. Thin-film evaporation is more efficient than evaporation from a deep-water layer because less energy is required to heat a small quantity of water. Materials such as cotton cloth, jute cloth, black fabric, sponge, charcoal cloth, and synthetic porous media have been used as wicks. In tubular solar stills, the wick can be placed over the absorber surface or arranged as a floating wick. The dark wick absorbs solar radiation and maintains a large wet surface for evaporation. However, wick materials may suffer from salt clogging, microbial growth, degradation, and reduced capillary performance over time. Hence, wick cleaning and material selection are important for long-term operation [21].

Thermal energy storage is also widely used to improve productivity, especially during evening and night hours. Phase change materials such as paraffin wax, stearic acid, lauric acid, and other organic PCMs absorb latent heat during daytime and release it after sunset. This stored heat maintains the water temperature for a longer duration and extends evaporation beyond peak sunshine hours. In tubular solar stills, PCM may be placed below the absorber basin, inside sealed tubes, or in contact with the absorber plate. The effectiveness of PCM depends on melting temperature, latent heat capacity, thermal conductivity, quantity, encapsulation method, and heat transfer contact with the basin. Since many PCMs have low thermal conductivity, fins, metal foam, nanoparticles, or conductive containers are often used to improve heat transfer.

Nanoparticles and nanofluids have been introduced to improve thermal performance by increasing solar absorption and thermal conductivity. Nanoparticles such as Al_2O_3, CuO, TiO_2, SiO_2, graphite, carbon black, graphene oxide, and carbon nanotubes can be dispersed in saline water or mixed with PCM. These particles improve heat transfer and may increase water temperature, resulting in higher evaporation rate. Black nanoparticles also improve volumetric solar absorption by converting radiation directly into heat within the fluid. However, nanoparticle use raises concerns related to dispersion stability, cost, sedimentation, environmental safety, and contamination of residual brine. Therefore, nanofluid-based enhancement requires careful evaluation before field application.

Reflectors and solar concentrators are used to increase the amount of solar radiation entering the tubular still. External mirrors, internal reflectors, parabolic concentrators, compound parabolic concentrators, and aluminium foil reflectors can direct additional radiation onto the absorber surface. Since tubular geometry can receive radiation from different directions, reflector integration may be particularly useful for improving morning and afternoon productivity. However, concentrators can also increase cover temperature and thermal stress. If the transparent cover becomes too hot, condensation decreases. Therefore, solar concentration should be combined with condensation enhancement or cover cooling to maintain a favourable water-cover temperature difference.

Condensation enhancement is equally important because higher evaporation alone does not guarantee higher freshwater output. If vapour is not effectively condensed, productivity remains limited. Cover cooling methods include flowing a thin water film over the outer cover, air cooling, forced convection, external cooling jackets, or attaching external condensers. Cooling the cover increases the temperature difference between vapour and condensing surface, improving condensation rate. However, excessive cooling may reduce internal temperature and evaporation if not properly controlled. External condensers can separate the evaporation and condensation zones, allowing better thermal management. In tubular solar stills, external condenser attachment can improve yield but increases system complexity and cost.

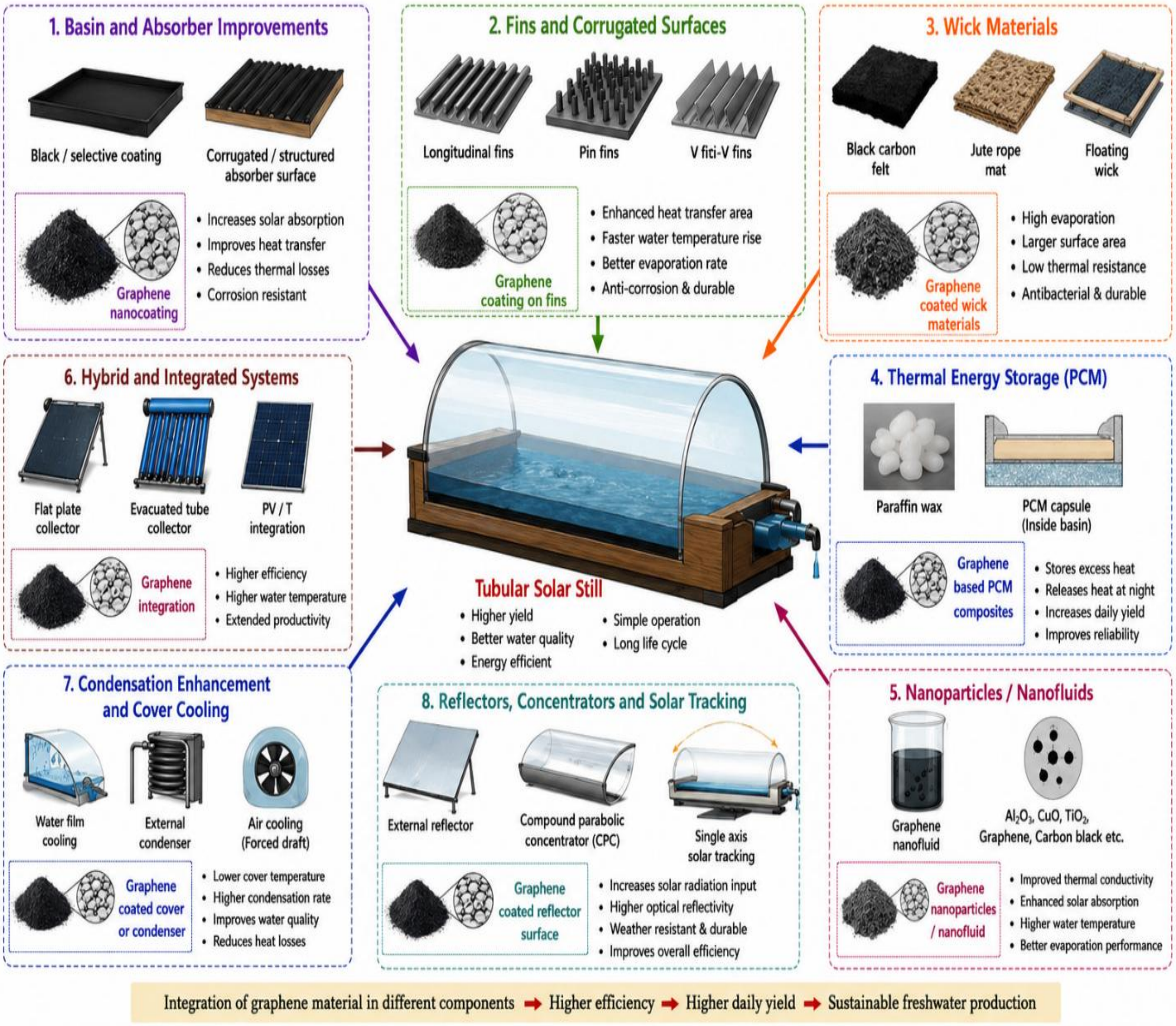

Fig. 2. Major design and development approaches for productivity enhancement of tubular solar stills, including absorber modification, fins, wick materials, PCM, Graphene based nanoparticles, reflectors, condenser cooling, and hybrid solar integration

Hybrid tubular solar stills combine passive distillation with additional energy sources or supporting devices. Integration with flat plate collectors, evacuated tube collectors, photovoltaic-thermal systems, heat pipes, solar air heaters, waste heat sources, or thermoelectric modules can significantly increase water temperature and productivity. Evacuated tube collectors are especially attractive because they provide high-temperature heat input with reduced thermal loss. Photovoltaic-thermal integration can generate electricity while using the recovered heat for desalination. Hybrid systems are more productive than passive designs but require more components, higher investment, and maintenance. Therefore, hybrid tubular solar stills are suitable where higher freshwater demand justifies additional cost.

Computational and optimization-based approaches are also becoming important in tubular solar still development. Computational fluid dynamics can be used to study vapour movement, temperature distribution, condensation behaviour, and internal heat transfer. Machine learning and statistical optimization methods can predict productivity based on climatic and operating parameters. Response surface methodology, artificial neural networks, genetic algorithms, and other optimization techniques can help determine optimum water depth, basin temperature, cover cooling rate, PCM quantity, reflector angle, and flow conditions. These tools reduce experimental cost and support better design development.

IV. COMPARATIVE DISCUSSION AND RESEARCH GAPS

The productivity improvement methods used in tubular solar stills differ in mechanism, cost, complexity, maintenance requirement, and suitability for practical application. Simple passive modifications such as reduced water depth, black absorber coating, improved insulation, and optimized basin geometry are low-cost and easy to implement. These methods are suitable for rural and household applications because they do not require external energy input or complicated maintenance. However, their productivity improvement is limited compared with advanced hybrid systems. Therefore, such techniques are best suited as baseline improvements that should be included in almost every tubular solar still design.

Fins, corrugated absorbers, and extended surfaces provide better heat transfer from absorber to saline water. These modifications are effective because they directly increase water temperature and evaporation rate. However, they may increase fabrication complexity and create locations for salt deposition. In saline operation, salt crystals may accumulate around fins and reduce heat transfer effectiveness. Therefore, finned tubular solar stills require proper cleaning access and corrosion-resistant materials. Copper and aluminium fins provide high thermal conductivity, but their cost and corrosion behaviour must be considered. For low-cost applications, galvanized iron or coated aluminium may be preferred, but long-term durability must be experimentally verified.

Wick materials offer strong productivity improvement because they convert bulk water evaporation into thin-film evaporation. This is particularly useful in tubular solar stills because the internal curved enclosure can support compact wick arrangement. Floating wick designs can reduce the amount of water heated at one time, resulting in faster thermal response. However, wick-based systems are sensitive to salt clogging, wetting uniformity, material degradation, and biological contamination. Natural wicks such as jute and cotton are inexpensive but may degrade faster. Synthetic wicks may last longer but can increase cost. Future research should focus on washable, durable, salt-resistant, and low-cost wick materials suitable for long-term field use.

Phase change materials are useful for extending productivity after sunset. In conventional passive stills, water production decreases rapidly when solar radiation falls. PCM stores excess heat during peak sunshine and releases it during low-radiation periods. This makes the system more stable and improves total daily yield. However, PCM-based systems must be carefully designed because unsuitable melting temperature can reduce effectiveness. If the PCM melting point is too high, it may not fully melt during normal operation. If it is too low, heat may be released too early. Another limitation is low thermal conductivity of many PCMs, which slows charging and discharging. Therefore, future designs should combine PCM with fins, conductive containers, metal foam, or nano-enhanced PCM while maintaining reasonable cost.

Nanoparticles and nanofluids show promising thermal enhancement but require deeper practical investigation. They can improve solar absorption and thermal conductivity, but long-term stability remains a major issue. Nanoparticles may settle, agglomerate, or deposit on basin surfaces. If nanoparticles are mixed directly with saline water, there may be concern regarding disposal of concentrated brine containing nanoparticles. If nanoparticles are mixed with PCM, leakage and compatibility with encapsulation materials must be considered. Therefore, although nanotechnology can improve performance in controlled experiments, field-level environmental and economic assessment is necessary.

Reflectors and concentrators can substantially increase solar input, especially in regions with high direct normal irradiation. They are attractive because they use simple optical redirection rather than electrical energy. Nevertheless, solar concentration may also increase cover temperature, thermal stress, and material degradation. A high absorber temperature improves evaporation, but a high cover temperature reduces condensation. Therefore, reflector-based tubular solar stills should be designed with proper cover cooling or external condensation. Manually adjusted reflectors are low cost but require user involvement. Tracking systems improve radiation capture but increase cost and mechanical complexity.

Condensation enhancement methods such as cover cooling and external condensers can significantly improve freshwater output when evaporation rate is already high. In many solar still designs, condensation becomes the limiting process during peak sunshine because the cover temperature rises. A water film flowing over the outer cover can reduce cover temperature and improve condensation. However, this method consumes cooling water, and if the cooling water

ISSN : 2455-9679
SJIF Impact Factor : 6.190

becomes warm, its effectiveness decreases. External condensers improve vapour condensation by providing additional cooled surface area, but they increase size and complexity. A well-designed tubular solar still should maintain balance between evaporation enhancement and condensation control.

Hybrid systems using evacuated tube collectors, flat plate collectors, photovoltaic-thermal panels, heat pipes, or waste heat can achieve higher productivity than purely passive stills. Such systems are suitable for applications requiring larger freshwater output. However, their cost, maintenance, and installation requirements are higher. The main challenge is to ensure that the additional productivity justifies the additional cost. Techno-economic analysis, payback period, cost per litre, and life-cycle assessment must therefore be included in future studies. Many experimental studies report improved productivity, but fewer studies provide complete economic and long-term durability analysis.

Several research gaps remain in the development of tubular solar stills. First, many studies are conducted under specific climatic conditions, making it difficult to compare results across different regions. Standardized testing methods are required for meaningful comparison. Second, long-term outdoor testing is limited. Many materials perform well for a few days or weeks but may degrade under prolonged exposure to solar radiation, salinity, humidity, and thermal cycling. Third, salt scaling and cleaning methods are not sufficiently addressed. Since solar stills concentrate salts continuously, practical designs must allow easy brine removal and surface cleaning. Fourth, cost analysis is often incomplete. Productivity improvement alone is not enough; the cost per litre of freshwater must also be low.

Fifth, many studies focus on single enhancement techniques, whereas real productivity improvement requires integrated design. For example, PCM improves night-time operation, but it may be more effective when combined with fins. Wick materials improve evaporation, but condensation cooling may be required to convert additional vapour into freshwater. Reflectors increase solar input, but cover cooling may be necessary to maintain condensation. Therefore, future tubular solar still development should focus on optimized combinations rather than isolated modifications. Sixth, computational modelling must be more strongly validated with experimental data. CFD and machine learning can support design optimization, but their predictions must be tested under real operating conditions.

The future of tubular solar stills lies in the development of low-cost, durable, modular, and easy-to-maintain designs suitable for diverse applications. For rural and decentralized use, passive systems incorporating shallow water depth, efficient wick materials, proper insulation, simple reflectors, and advanced graphene-based nano-coating on absorber surfaces are highly promising. The use of graphene coatings enhances solar absorptivity, thermal conductivity, and corrosion resistance, thereby improving evaporation rates and overall system efficiency. For applications requiring higher productivity, advanced configurations such as phase change materials (PCM), external condensers, evacuated tube collectors, and photovoltaic-thermal (PVT) integration can be employed. The selection of an appropriate design should be based on local climatic conditions, water demand, economic feasibility, material availability, maintenance capabilities, and user skill level. Incorporating graphene nanomaterials in both passive and active systems offers a significant opportunity to bridge the gap between performance enhancement and cost-effectiveness, making tubular solar stills more viable for large-scale and rural deployment.

V. CONCLUSIONS

Tubular solar stills represent a promising passive solar desalination technology for producing freshwater from saline, brackish, or contaminated water. Their curved transparent cover, increased condensation area, compact geometry, and modular nature provide important advantages over conventional basin-type solar stills. However, the productivity of a basic tubular solar still remains limited due to low evaporation rate, heat losses, high cover temperature, poor condensation control, salt deposition, and limited night-time operation. Therefore, several design and development approaches have been investigated to improve freshwater yield and overall thermal performance.

The review shows that productivity enhancement can be achieved through multiple pathways. Optimized water depth reduces thermal inertia and improves evaporation response. Absorber surface modification, particularly using advanced materials such as graphene-based nano-coatings, significantly improves solar radiation absorption and basin-water heat transfer due to their high thermal conductivity and superior absorptivity. Fins and corrugated surfaces increase heat transfer area and raise water temperature. Wick materials improve thin-film evaporation and reduce the amount of water heated at one time. Phase change materials store excess heat and extend productivity beyond sunshine hours.

Nanoparticles, especially graphene based nanomaterial, enhance thermal conductivity and solar absorption, although their stability and environmental impact must be carefully addressed. Reflectors and concentrators increase solar input, while cover cooling and external condensers improve condensation. Hybrid systems using solar collectors, evacuated tubes, photovoltaic-thermal modules, and waste heat can provide higher productivity but involve greater cost and complexity.

Among these methods, the most practical approach is not a single modification but a balanced integration of evaporation enhancement, thermal storage, solar radiation improvement, and condensation control. For low-cost rural applications, passive designs using shallow water depth, graphene-coated absorber surfaces, wick materials, proper insulation, and simple reflectors may be most suitable. For higher freshwater demand, hybrid tubular solar stills incorporating graphene-based nanomaterials along with PCM, external condensers, or solar collectors may be more effective. However, future research must focus on long-term durability of graphene coatings, salt scaling control, cost per litre, life-cycle assessment, standardized testing, and field validation under real climatic conditions. A technically successful tubular solar still must not only produce more freshwater but also remain affordable, durable, easy to clean, and suitable for local users.

Tubular solar stills have strong potential for sustainable small-scale desalination, especially in regions with abundant solar radiation and limited freshwater access. Continued research on advanced material selection, particularly graphene-based coatings and nanofluids, along with heat transfer enhancement, condensation improvement, and integrated passive-hybrid designs, can significantly improve system efficiency and make tubular solar stills more practical and scalable for decentralized freshwater production.

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