

**EFFECT OF SURFACE MORPHOLOGY ON THE PERFORMANCE
OF ADDITIVELY MANUFACTURED SOLAR STILLS**

BY

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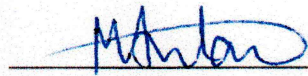
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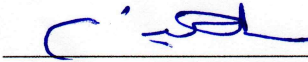
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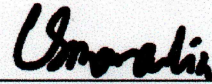
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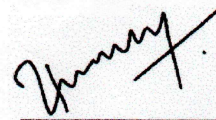
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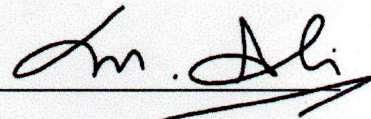
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2025

I dedicate this thesis to my parents, whose unwavering love, encouragement, and sacrifices have been the guiding light throughout my academic journey. Their boundless support and belief in my abilities have fueled my determination to pursue excellence in every endeavor. From the earliest days of my education to the culmination of this thesis, their strength, wisdom, and enduring faith have been my greatest sources of inspiration. This thesis is a tribute to their enduring presence in my life, and I am forever grateful for their selfless devotion and endless love. I am profoundly grateful for their sacrifices, understanding, and constant motivation, without which this achievement would not have been possible.

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LIST OF ABBREVIATIONS

AM	:	Additive Manufacturing
AMF	:	Additive Manufacturing File Format
BJ	:	Binder Jetting
CAD	:	Computer Aided Design
DED	:	Directed Energy Deposition
DLP	:	Digital Light Processing
DSC	:	Differential scanning calorimetry
FDM	:	Fused Deposition Modeling
FFF	:	Fused Filament Fabrication
FTIR	:	Fourier transform infrared spectroscopy
LENS	:	Laser Engineered Net Shaping
LMD	:	Laser Metal Deposition
MJ	:	Material Jetting
ME	:	Material Extrusion
PBF	:	Powder-bed Fusion
PLA	:	Polylactic Acid
SL	:	Sheet Lamination
SLA	:	Stereolithography
SS	:	Solar stills
STL	:	Standard Triangle Language
TGA	:	Thermogravimetric analysis
UV-Vis	:	Ultraviolet Visible Spectroscopy
VP	:	Vat Photopolymerization
XRD	:	X-ray Diffraction

ABSTRACT

Full Name : Murad Hassan S Alzahrani

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The AM process has revolutionized modern manufacturing by enabling the fabrication of complex geometric shapes in a number of fields. Among the different AM technologies, FDM is widely used for its cost-effectiveness and simplicity. In this work, an AM SS desalination device was constructed to address the urgency of the global water crisis. The effect of different surface morphologies covers (Glass and Acrylic), and water levels were studied. The AM PLA basin was performed. Material characterizations such as XRD, FTIR, DSC and TGA analysis were performed to analyze the phases, thermal properties, and chemical groups in the AM PLA basin. Contact angle and UV-Vis (absorption, transmittance) measurements were conducted on the glass and acrylic covers to assess their optical and surface properties. The SS experiments were conducted to assess the optimal cover followed by experiments to find the optimal water level and basin geometry. The results concluded that acrylic cover with 100 mL water and sinusoidal basin resulted in the most optimal SS. This research aims to contribute to the development of AM SS that promote scalable desalination technologies.

ملخص الرسالة

الاسم الكامل : مراد بن حسن بن سعيد الزهراني

عنوان الرسالة : تأثير شكل القاعدة على أداء أجهزة التقطير الشمسية المصنعة بتقنية التصنيع الإضافي

التخصص : الهندسة الميكانيكية

تاريخ الدرجة العلمية : مايو ٢٠٢٥

لقد أحدثت عملية التصنيع الإضافي (AM) ثورة في التصنيع الحديث من خلال تمكين إنتاج أشكال هندسية معقدة في العديد من المجالات. ومن بين تقنيات التصنيع الإضافي المختلفة، تُعد تقنية النمذجة بالتكديس المنصهر (FDM) الأكثر استخدامًا لما تتمتع به من فعالية من حيث التكلفة وسهولة التشغيل. في هذا العمل، تم إنشاء جهاز تحلية شمسي باستخدام التصنيع الإضافي (AM SS) لمعالجة أزمة المياه العالمية المتزايدة. تمت دراسة تأثير أشكال السطح المختلفة، وأنواع الأغشية (الزجاج والأكريليك)، ومستويات الماء المختلفة. وقد تم تصنيع الحوض من مادة PLA باستخدام تقنية التصنيع الإضافي. كما أُجريت تحليلات توصيف المواد مثل حيود الأشعة السينية (XRD)، و تحويل فورييه الطيفي بالأشعة تحت الحمراء (FTIR)، والتحليل مسعر متبايني (DSC)، والتحليل الوزني الحراري (TGA) لدراسة الأطوار البلورية والخصائص الحرارية والمجموعات الكيميائية في حوض PLA المصنوع. كما تم إجراء قياسات زاوية التلامس، وقياسات الامتصاص، والنفاذية، والانعكاس باستخدام جهاز UV-Vis على الأغشية الزجاجية والأكريليك لتقييم خصائصها البصرية والسطحية. وقد أُجريت تجارب التحلية الشمسية لاختيار الغطاء الأمثل، ثم تجارب لتحديد مستوى الماء الأمثل وشكل هندسة الحوض الأمثل. أظهرت النتائج أن استخدام غطاء من الأكريليك مع ١٠٠ مل من الماء و سطح حوض متموج (sinusoidal) يعطي أفضل أداء في عملية التحلية الشمسية. ويهدف هذا البحث إلى المساهمة في تطوير تقنيات تحلية شمسية (Solar Still) باستخدام التصنيع الإضافي لتكون قابلة للتوسع.

CHAPTER 1

INTRODUCTION

1.1 Background

Additive Manufacturing (AM) is the process of fabricating three-dimensional objects by layering materials incrementally until the desired shape is formed. This technology is applied in industries such as aerospace, healthcare, and oil & gas, where the reliability and performance of AM components are crucial considerations [1]. These industries require stringent quality standards and certifications for mission-critical applications. At present, components demanding high precision and durability often avoid using AM as the primary manufacturing method due to defects that can arise during the production process [2]. In response to these challenges, researchers are dedicating efforts to refining process parameters by investigating the intricate relationship between the process, structure, and properties of AM parts. Achieving optimal results involves considering various factors, such as material selection, the type of AM technology used, and post-production treatments, requiring a systematic approach to ensure high-quality, defect-free parts [3].

There are multiple categories of AM technologies, including BJ, DED, PBF, MJ, ME SL, and VP [4]. Among these, Material Extrusion—commonly known as FDM—is one of the most widely used methods. In FDM, a thermoplastic filament is heated and extruded through a nozzle, with each layer being deposited sequentially to create the final structure. Its widespread use can be attributed to its affordability and simplicity, making it a popular choice for both individual hobbyists and large-scale industrial manufacturers [5].

Clean water ranks as the second most critical need for all life forms on Earth [6]. Water holds paramount importance as a vital fluid, second only to air, in ensuring human survival [6]. Although clean water is crucial for human survival, only around $\sim 0.01\%$ of earth's water is accessible as surface water and about $\sim 2.8\%$ is classified as freshwater [7]. Also, about only 2.8% of usable water is in various forms, such as snow and groundwater. In contrast, the vast majority, around 97% of Earth's water is saline or brackish, found in seas, oceans, and some underground reservoirs. To make this water suitable for human consumption, extensive treatment processes are required.

Tragically, each year, 6~8 million individuals die from water-related health issues and natural disasters. These alarming statistics highlight an urgent need for researchers to find solutions for the global water crisis, exploring alternative sources of safe drinking water through renewable energy [7]. Desalination of saline or brackish water is a well-known approach to address this potable water shortage. Today, various desalination methods are available that meet the demand for drinkable water, bringing fresh water to regions in need.

Desalination techniques are divided into membrane and thermal-based methods. Membrane methods, like reverse osmosis, use selective membranes to separate salts, while thermal methods, such as SS, rely on heat to evaporate water. Understanding these approaches is crucial for selecting the best possible solution for solving the water scarcity around the world [8]. Recent advancements in AM have paved the way for innovative approaches to enhance the efficient of solar desalination. For example, Koh et al. [9] have developed hydratable plastics using FDM that facilitated efficient evaporation and

achieved successful desalination. Similarly, Cao et al. [10] utilized FDM to create tree-inspired, cone-shaped 3D Janus evaporators. Additionally, Kaviti et al. [11] conducted desalination by AM of micro- and nano-hierarchical pyramid-shaped structures on aluminum plates. These studies highlight the potential of AM techniques to improve evaporation rates and revolutionize solar desalination technologies.

This study will evaluate a SS desalination device incorporating components produced through AM technology. The device's efficiency will be assessed by examining the effects of cover materials, ambient conditions, and various surface morphologies. This research seeks to bridge the gap between advanced manufacturing techniques and renewable energy solutions, paving the way for more efficient and sustainable water desalination technologies. Through these objectives, the study aims to establish a foundation for further innovations in SS design and production.

1.2 Motivation

The global water crisis can be classified as one of the major global problems as millions of lives are jeopardized by the scarcity of safe drinking water. Traditional SS, while simple and renewable, often suffer from low efficiency due to suboptimal thermal management and evaporation rates. Recent breakthroughs in AM-enabled structures such as hierarchically porous evaporators, biomimetic designs, and surface-engineered components demonstrate remarkable potential to enhance the performance of SS. For instance, 3D-printed architectures can maximize light absorption, improve heat localization, and accelerate vapor condensation, addressing key limitations of conventional SS systems. However, the integration of AM into SS technology requires systematic

evaluation of critical parameters, including cover materials, ambient conditions, and surface morphology, to unlock its full potential.

1.3 Thesis objectives

The primary objective of this thesis is to evaluate the manufacturability and application of SS as efficient AM desalination devices. AM SS offer a sustainable and cost-effective solution for water desalination with opportunities to enhance the design and performance. The research focuses on understanding the usage of AM techniques to produce SS components and improve their operational efficiency. To achieve this overarching goal, the study is structured around the following specific objectives:

- Assessing the feasibility and manufacturability of SS components using AM techniques, with an emphasis on producing robust, lightweight, and intricate designs.
- Investigating the effects of cover materials and ambient environmental conditions (such as temperature, humidity, and solar intensity) on SS performance.
- Examining the impact of varying surface morphologies within the SS basin to enhance heat absorption and evaporation.

1.4 Methodology

The primary objective of this thesis is to enhance the efficiency of SS desalination systems through the integration AM technology. Different PLA basin geometries (flat, V-shaped, and sinusoidal) were fabricated via FDM AM to investigate their influence on evaporation rates and thermal management. Additionally, two transparent covers (glass and acrylic) were evaluated to assess their absorption and transmittance. Atmospheric parameters,

including wind velocity, ambient temperature, and solar irradiance, were systematically monitored to ensure the accuracy of the experimental results.

The structural, thermal, and chemical properties of the AM PLA bases were also investigated. TGA was employed to quantify thermal stability and decomposition behavior under an inert atmosphere. The DSC experiments were also conducted to study the glass transition, cold crystallization, and melting points, while also calculating the degree of crystallinity. Presence of crystalline phases and amorphous content was studied using XRD analysis. Complementary FTIR analysis identified functional groups and chemical bonding interactions, confirming the absence of degradation byproducts or residual monomers in the AM FDM substrates.

The glass and acrylic covers were subjected to UV-Vis spectroscopy and contact angle measurements to evaluate their optical performance and wettability. UV-Vis analysis quantified wavelength-dependent absorption and transmittance across the solar spectrum, enabling direct comparison of photon utilization efficiency. Concurrently, contact angle goniometry assessed surface hydrophilicity by measuring the equilibrium angle formed between distilled water droplets and the cover materials, providing insights into condensate adhesion and shedding dynamics.

The characterization results were used in conjunction with the SS experiments to investigate the impact of varying basin geometries (flat, V-shaped, and sinusoidal) on the performance of SS with different covers. The findings of this research are expected to offer valuable insights into enhancing SS efficiency through the application of AM technologies, thereby contributing to advancements in both solar desalination and AM processes.

CHAPTER 2

LITERATURE REVIEW

2.1 Additive manufacturing (AM)

The AM process has experienced remarkable advancements and is now recognized as a pivotal component of 4th industrial revolution [12]. AM, often referred to as 3D printing, is a production technique that builds three-dimensional objects by layering material incrementally. According to the ISO and ASTM 52900:2015 standard, AM is defined as a process in which materials are joined to create objects, layer by layer, based on specific geometries, distinguishing them from traditional formative or subtractive methods of manufacturing [4]. The typical AM workflow, outlined in Figure 2.1, includes several key steps: First, Initial design and conceptualization using CAD software like SolidWorks© or AutoCAD to develop a digital model. This stage can also involve reverse engineering to recreate existing parts. Second, conversion of the digital design into STL or AMF file formats, followed by preprocessing. During this step, the model is sliced into layers suitable for printing, and support structures are generated to maintain geometric integrity. Third, file transfer to the AM machine can be done via direct connections, wireless networks, or removable storage. Fourth, machine setup and file preparation, where the sliced file is uploaded, and printing parameters are configured. Fifth, part fabrication begins, and once complete, the part is removed and goes through post-processing, including cleaning and additional finishing steps.

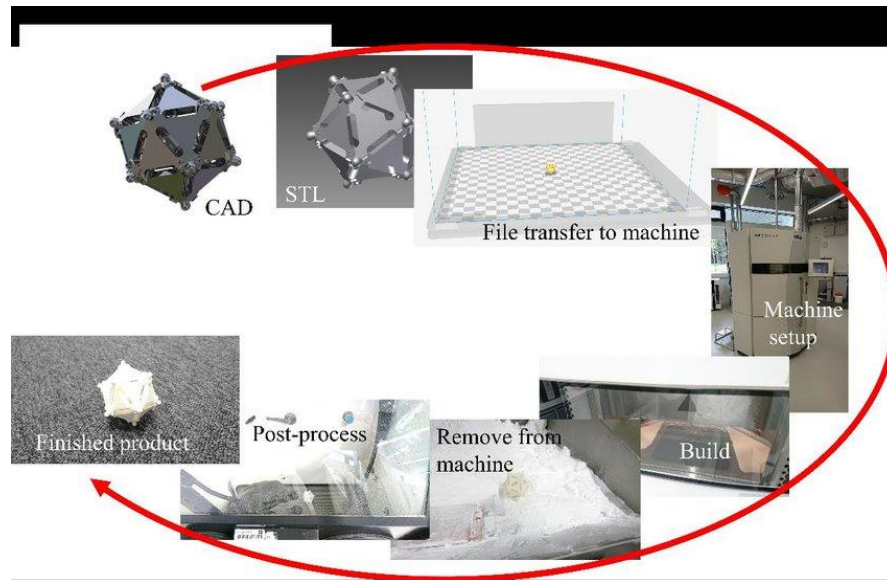


Figure 2.1: Generic process cycle for AM [13].

Additive manufacturing process have gained widespread adoption across numerous industries, thanks to its design versatility, faster production times, and ability to create intricate geometries [5]. AM is commonly utilized for applications such as prototyping, product customization, and low-volume production runs [14]. Furthermore, the capability to work with a diverse range of materials has positioned AM as a cutting-edge technology with great potential for future advancements. This has led to its growing use in sectors like aerospace [15], automotive [16], healthcare [17], and consumer products [18], where innovation and efficiency are critical drivers of success.

2.2 Process classifications

The ISO/ASTM 52900:2015 standard has seven distinct groups of AM processes. These classifications include ME, BJ, VP, PBF, MJ, SL, and DED [4]. Each of these groups utilizes unique methods and technologies for building three-dimensional objects by layering materials, with specific techniques tailored to each process, as outlined below:

2.2.1 Material Extrusion (ME)

The ME process involves the use of a thermoplastic filament that is heated and pushed through a nozzle to form the desired structure [19]. The basic operation of the ME process is illustrated in Figure 2.2. This technique is often employed for producing large-scale components or prototypes with relatively simple designs. Two of the most widely recognized ME methods are FFF and FDM [19]. A dual material extrusion technique has also been utilized to develop bio-inspired structures that are both lightweight and impact resistant. This method leverages multi material printing, allowing for the combination of rigid and flexible materials within a single structure, a design approach often seen in nature. Despite these benefits, the process still faces challenges such as limited surface quality, slow production speeds, and dimensional constraints [20]. Nevertheless, material extrusion has become widely adopted, thanks in part to the availability of affordable materials and nozzles, as well as its adaptability in both hardware and software configurations [21].

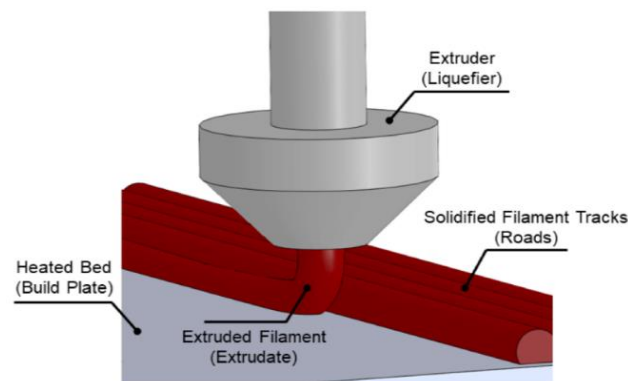


Figure 2.2: Working principle of ME process [19].

2.2.2 Binder Jetting (BJ)

The BJ process employs a powder-based material that is selectively fused using a liquid binder to form the intended shape. The general workflow of the BJ process is depicted in Figure 2.3. This technique is particularly effective for producing parts that require intricate

details and customization. Its cost-effectiveness and high throughput make BJ a highly promising method for large-scale production [22]. Several factors such as the binder, the morphology of powder particles, and speed influence the performance of BJ parts. Therefore, the interaction between the binder and the powder is crucial in determining the final part's strength and integrity [23]. Additionally, post-processing techniques play a significant role in enhancing the properties of the printed part, as these steps are often necessary to achieve the desired density and mechanical characteristics. All of these factors must be carefully controlled to ensure optimal outcomes in BJ [23].

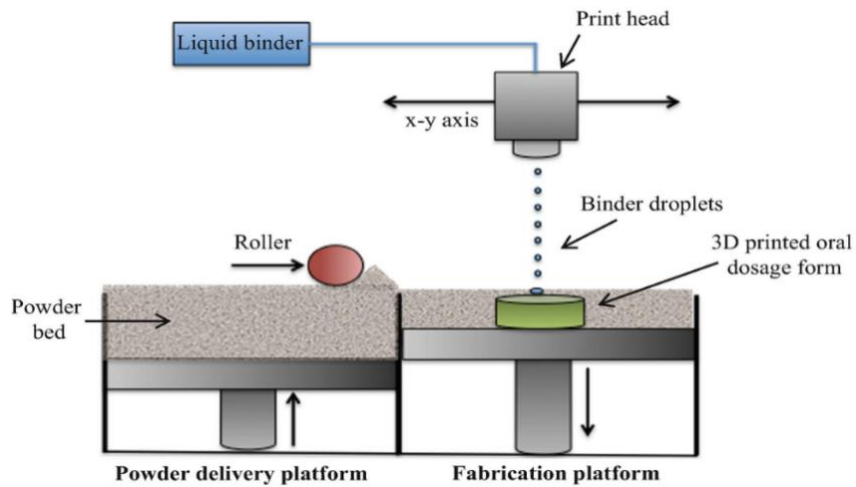


Figure 2.3: General schematic of the BJ process [22].

2.2.3 Vat Photopolymerization (VP)

VP involves the use of a liquid photopolymer resin that is cured by a focused light source to build up the desired object. This technique is well-suited for producing high-resolution parts, including items like dental implants and jewelry [24]. Common VP methods include SLA and DLP. Figure 2.4 illustrates the operational principles of both SLA and DLP processes [24]. In this process, ultraviolet (UV) light is used to initiate a chain reaction within a layer of monomer solution. The UV-sensitive monomers convert into polymer

chains once exposed to light. As polymerization occurs, a solid pattern is formed in the resin, which supports the following layers during the building process. After printing is complete, any unreacted resin is removed from the final structure [25]. Some printed parts may require additional treatments, such as heating or exposure to UV light, to enhance their mechanical properties [25].

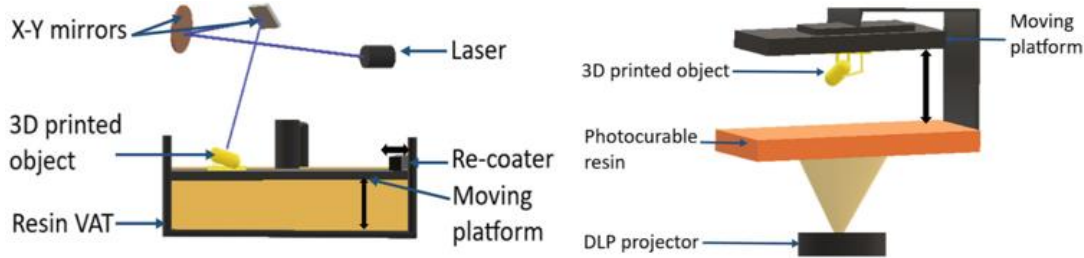


Figure 2.4: Working principle of VP process (SLA and DLP) [24].

2.2.4 Powder-bed Fusion (PBF)

The PBF process involves a bed of powder material that is selectively fused by a heat source, such as a laser or electron beam, to form the desired object [26]. This process can utilize either metal or polymer powders as feedstock. The fundamental operation of PBF is illustrated in Figure 2.5. PBF is known for its ability to produce parts with complex geometries, high accuracy, and substantial strength [26]. Notable examples of PBF techniques include Laser Powder-Bed Fusion (LPBF), Selective Laser Melting (SLM), Selective Laser Sintering (SLS), and Electron Beam Melting (EBM) [26]. Key factors that impact the efficiency of PBF are the distribution and packing of the powder particles, both of which significantly influence the density of the final printed part. The two most crucial parameters that affect the sintering process are laser power and scanning speed [27]. This fine resolution and high print quality achieved by PBF make it ideal for creating intricate designs with small, precise details. One of the notable advantages of the PBF process is the

use of the powder-bed as a support, removing the need for additional support materials. However, the technique does come with some drawbacks, including longer production times, higher costs, and the risk of increased porosity when using binder-infused powders [27]. Examples of materials like titanium alloys and amorphous calcium polyphosphate have been successfully used to create biomimetic designs, demonstrating adequate mechanical performance for applications requiring lightweight structures and energy absorption [28].

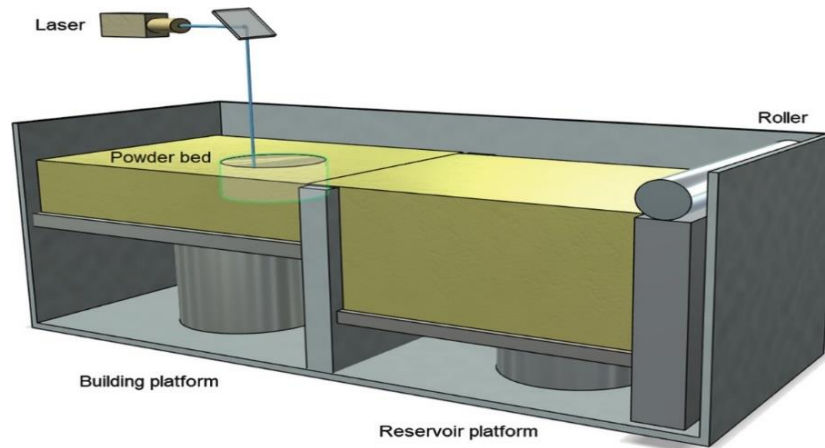


Figure 2.5: Basic representation of the PBF process [26].

2.2.5 Material Jetting (MJ)

MJ process involves the use of a print head to eject droplets of liquid materials, such as wax or resin, which are then cured to solidify and build up the part. The operational principles of the MJ process are depicted in Figure 2.6. This method is particularly effective for producing high-resolution components with intricate designs. Common examples of MJ techniques include PolyJet and Multi-Jet Fusion [29]. Despite its advantages, MJ remains a relatively expensive option in comparison to other AM techniques because the MJ process utilizes photosensitive resins and therefore require post-processing [25]. Multi-

material inkjet printing is one of the latest MJ techniques that opens up opportunities to create robust and tough structures from monomer inks that would typically result in either weak and flexible or brittle and rigid materials [30].

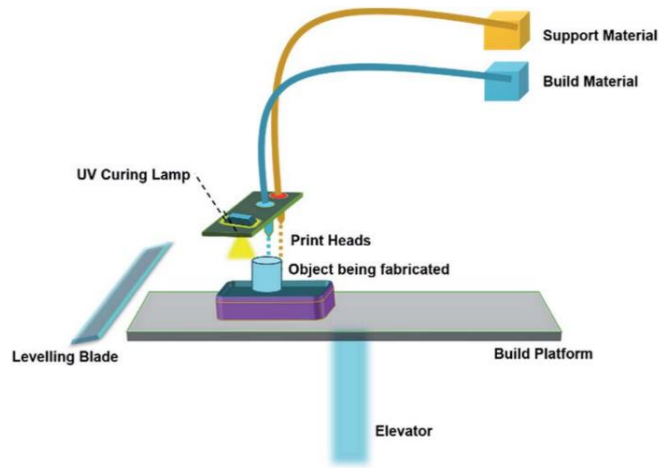


Figure 2.6: Working principle of MJ process [29].

2.2.6 Sheet Lamination (SL)

SL distinguishes itself from other AM methods by starting with thin sheets of material, such as paper or metal foil, rather than using liquids or powders. These sheets are stacked and bonded together using adhesive or heat, with each layer then cut or trimmed to achieve the final shape of the part [31]. This technique is often employed for producing large-scale models or prototypes. Figure 2.7 illustrates the basic principles of the SL process. Similar to the dry preform process, the composite SL process builds by stacking sheets of fiber-reinforced polymers. However, the sheet materials used in this process must should easily rolled, compressed and cut to meet the required specifications. Certain challenges arise during composite fabrication through pressing, including shrinkage, warping, delamination, and shape distortion [32]. Despite these challenges, the pressing process

allows for the production of parts with qualities similar to those achieved through traditional manufacturing methods [32].

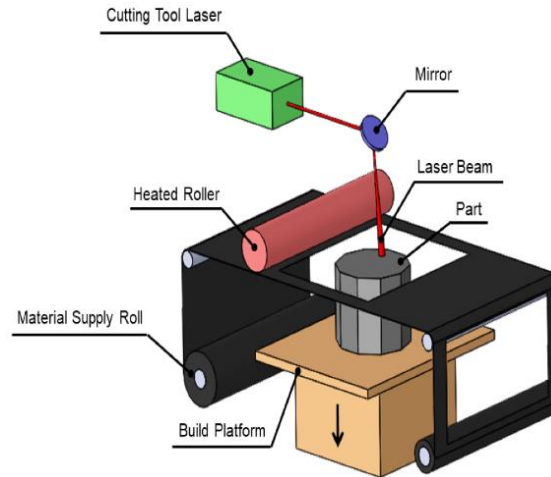


Figure 2.7: Working principle of SL process [31].

2.2.7 Direct energy deposition (DED)

The DED process utilizes a concentrated energy source, such as a laser or electron beam, to melt and deposit powder or wire material onto a substrate. The feedstock material is introduced through a nozzle before being melted in this process [19]. The operational details of the DED process are depicted in Figure 2.8. This technique is frequently applied for repair work or the construction of large-scale structures. Examples of DED methods include LMD and LENS [33]. Metal powders are commonly utilized in DED processes such as copper, titanium, cobalt, stainless steel, aluminum, and nickel [33]. Nonetheless, other materials such as polymers, ceramics, and metal matrix composites are also viable options for this technique [34].

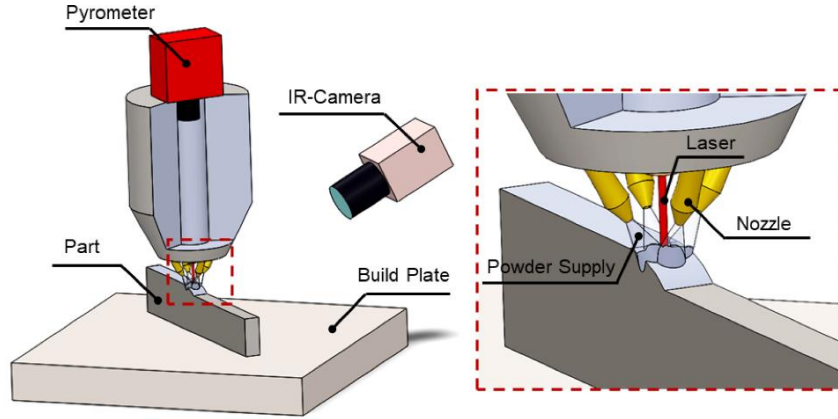


Figure 2.8: Working principle of DED process [19].

2.3 Feedstock materials for AM

Feedstock materials for AM processes come in various forms, including resin [35], powder [36], wire [37], filament [38], and spools [39]. These materials are generally grouped into four main categories: polymers [40], metals [15], ceramics [41], and composites [16]. Each type possesses distinct properties that make it suitable for different applications. Polymers are the most widely used due to their affordability, flexibility, and ease of processing [42]. Metals are preferred for manufacturing parts requiring high strength, durability, and resistance to extreme temperatures [15]. Ceramics provide excellent thermal stability, chemical resistance, and electrical insulation [41]. Composites are used for producing lightweight, strong parts with specialized properties [16]. As AM technology advances, new materials continue to be developed, expanding the possibilities of the field. Given the focus of this work on polymers, Figure 2.9 outlines the classifications of polymer feedstock based on their fusion state, feedstock form, material distribution method, AM processing principles, and specific categories.

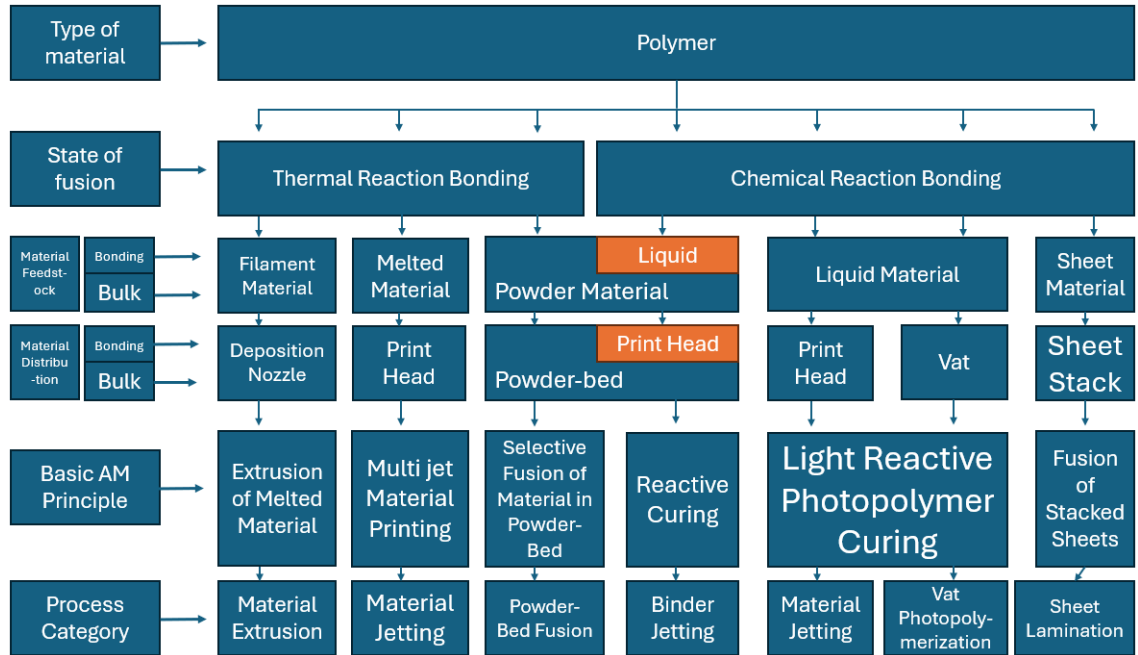


Figure 2.9: Polymer feedstock classifications in AM [42].

2.4 Fused Deposition Modeling (FDM)

In FDM, a heated nozzle moves to deposit molten polymer material onto a base, typically using a filament as feedstock. The material is heated slightly above its melting point inside the print head before being extruded through the nozzle onto a substrate, where it rapidly cools and hardens to form a layer that mirrors the cross-section of the design [31]. This process is repeated layer-by-layer until the entire object is fully built, as demonstrated in Figure 2.10. Advancements in the FDM process have led to the development of multi-nozzle FDM systems, where each nozzle extrudes different materials, enabling the production of parts with distinct material properties [41].

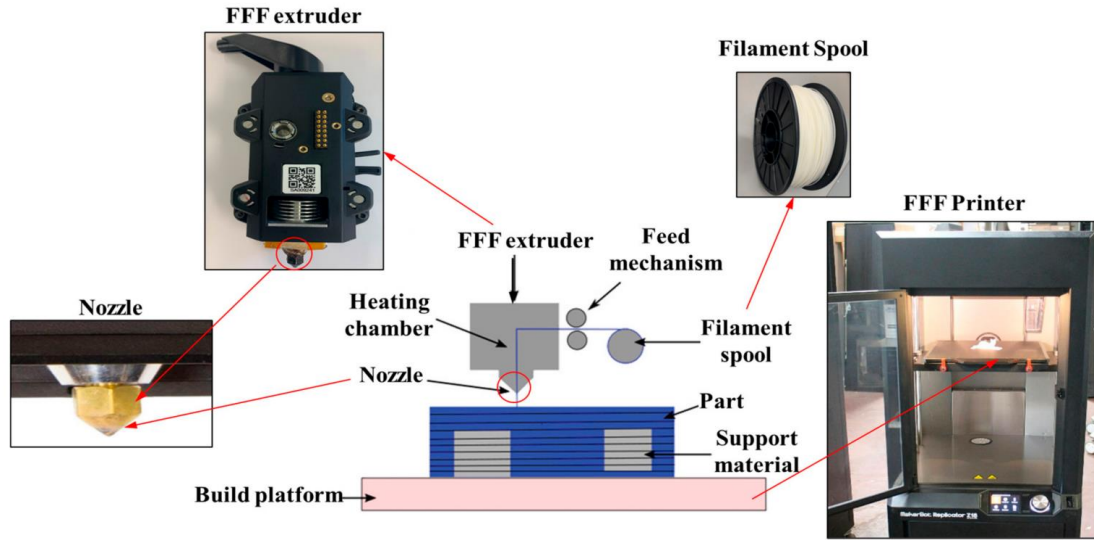


Figure 2.10: FDM printer components [43].

Similar to other AM methods, the quality of parts produced through the FDM process is significantly influenced by various process parameters. These parameters play a crucial role in determining the final part's performance and structural integrity. The key FDM process parameters fall into three main categories: slicing parameters, part orientation, and temperature settings. Each of these factors contributes to the overall quality and precision of the printed object. Layer thickness, raster width and print speed are some of the most commonly used slicing parameters while orientation, nozzle and bed temperatures are used as print and temperature settings during the FDM process [44], [45].

The FDM process primarily utilizes thermoplastic materials, with the most frequently studied in research being Acrylonitrile Butadiene Styrene (ABS), PLA, polyethylene terephthalate glycol (PETG), and Nylon [45]. ABS is known for its strength and durability, making it a popular choice in automotive and industrial applications [46]. PLA, a biodegradable thermoplastic, is favored for its ease of use and excellent dimensional

stability during printing [47]. PETG is recognized for its flexibility and toughness, making it suitable for packaging and various consumer products [48]. Nylon stands out for its strength and flexibility, making it ideal for functional components that require high wear resistance [49]. An overview of the commonly used and specialty materials utilized in FDM printing is provided in Table 2.1.

Table 2.1: FDM filament materials [45].

Material	Source	Advantages	Disadvantages	Temperature
ABS	Petroleum	Good toughness, cheap	Warpage, unpleasant gases	210-250°C
PLA	Plant starch	Biodegradable, less warpage, cheap	Low mechanical strength, brittle	190-230°C
PEEK	Bisphenolate	High strength, light, chemically resistant	High print temperature, costly, warpage	360-420°C
Nylon	Crude oil	Good mechanical strength, cheap, wear resistance	Warpage, high print temperature	240-270°C

2.5 Solar stills (SS)

Water is an essential element in the development of human civilization and is indispensable for the continuation of life. In the human body, water plays a pivotal role in several vital functions, such as blood circulation, digestion, and waste disposal. The quality of water is highly dependent on its use. However, drinking water must be pure and free of pollutants, and viruses to maintain human health and safety [50].

Many developing nations are grappling with limited access to safe drinking water. In these areas, natural water sources are unable to keep up with the growing demands, leading to a critical shortfall of clean water needed for daily human activities [50]. The world health organization reports that approximately 2.6 billion people worldwide do not have access to

safe drinking water. Unsafe water and poor sanitation conditions leads to over 1.6 million deaths annually due to diarrhea, with children under the age of five accounting for 90% of these fatalities. The lack of clean water remains a significant public health issue, disproportionately affecting vulnerable populations [51]. Topographical studies indicate that over two-thirds of the earth's surface is covered by water. However, about 97% of this water is saline, 2.6% is locked in ice, and less than 1% is freshwater accessible for human use [52]. With the global population steadily increasing, the demand for water is rising at a significant rate. Ensuring an adequate supply of water, both in terms of quantity and quality, has become a pressing concern. Projections suggest that by 2025, nearly every individual will experience some level of water stress due to limited resources [52].

Water security encompasses a wide array of critical dimensions that are essential for sustainable development. Effective management of transboundary water resources is vital for ensuring equitable access and fostering collaboration between nations, reducing the likelihood of conflicts over shared water supplies. Maintaining water quality is critical to protecting public health and preserving ecosystems. In residential areas, increasing population requires the development of infrastructure and efficient water management systems to meet growing needs [50]. From an economic view (Figure 2.11), achieving water security is fundamental to the success of the agricultural and industrial sectors. A holistic approach that incorporates these dimensions into policy-making is essential to achieving water security and meeting long-term sustainable development objectives, ensuring that water resources are protected for future generations [50].

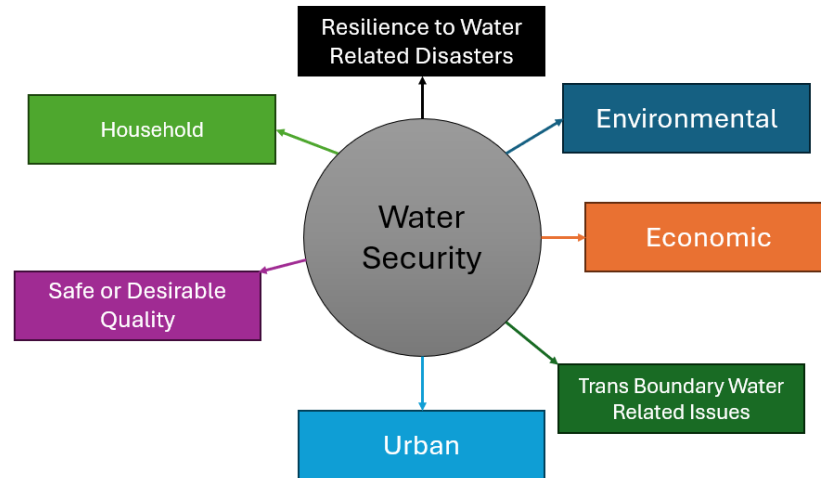


Figure 2.11: Important issues in water security [53].

Solar energy plays a critical role in natural processes such as climate regulation, wind patterns, precipitation, and photosynthesis. Solar power is converted into heat, which drives numerous vital activities and systems on earth [54]. As a renewable, abundant, and environmentally friendly resource, solar energy offers a viable alternative to fossil fuels, which are known to contribute to environmental degradation [55]. Utilizing this accessible and clean energy source is crucial for securing a sustainable future. In essence, solar energy underpins all forms of energy on Earth. Likewise, solar radiation causes temperature variations that result in wind, driving wind turbines and generating wind energy. Embracing solar energy, therefore, is a step toward reducing reliance on harmful energy sources and preserving the environment for future generations [55].

2.5.1 Desalination techniques

Desalination has been identified as a viable solution for addressing global water scarcity, particularly in regions with limited access to freshwater sources. This process, which involves converting seawater into drinkable water, is achieved by removing salts and other impurities. The methods of desalination are generally classified into two primary

categories: membrane-based techniques and thermal-based techniques (Figure 2.12) [8]. Each approach operates on distinct principles and is used in different contexts depending on factors such as resource availability and cost. Evaluating these methods in terms of their operational processes, efficiency levels, and environmental impact is critical for determining their feasibility and potential in alleviating water shortages. Gaining a detailed understanding of both membrane and thermal desalination techniques is essential for making informed decisions about their adoption and long-term sustainability [8]. Figure 2.12 shows the various desalination processes.

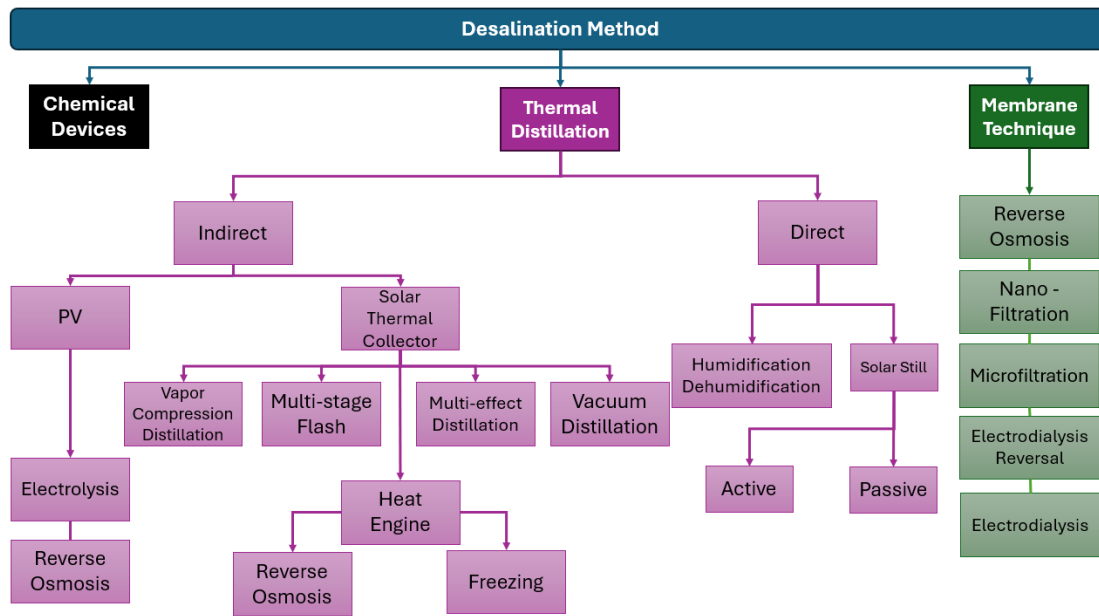


Figure 2.12: Classification of desalination processes [8].

(a) Membrane-based methods

Membrane-based desalination methods have gained significant importance in efforts to combat global water shortages. These methods utilize semi-permeable membranes that allow water to pass through while blocking salts and impurities, making them an energy-efficient solution for purifying seawater. By employing advanced filtration techniques,

membrane-based processes are seen as not only effective but also more environmentally friendly compared to other desalination technologies. The growing focus on these methods is driven by their potential to provide sustainable access to potable water, particularly in regions experiencing severe water scarcity [8]. Some of the membrane-based methods include (a) Membrane distillation, (b) Electrodialysis, and (c) Reverse osmosis and are discussed below.

Membrane Distillation (MD) is a thermally driven process that employs a membrane to facilitate the separation of water from dissolved salts and other impurities. The process is based on a vapor pressure gradient, which is established by maintaining a temperature difference across a hydrophobic membrane [56]. The hydrophobic nature of the membrane prevents liquid water from passing through, while allowing water vapor to move across the membrane's pores [57]. This technique results in the production of high-purity freshwater, achieving rejection rates exceeding 99%, making it highly effective in water purification [58]. MD systems are divided into four primary types: Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweeping Gas Membrane Distillation (SGMD), and Vacuum Membrane Distillation (VMD) [59]. DCMD is widely preferred, especially for treating brine, due to its simplicity and effectiveness in handling high salinity solutions. Each configuration offers unique advantages depending on the specific application and operational requirements [59]. In DCMD, the feed brine is initially heated before interacting with the membrane. The warm brine flows along one side of the membrane, causing vapor to pass through the membrane's pores. On the opposite side, this vapor condenses into freshwater, resulting in the production of clean distillate. The concentrated brine is retained by the membrane, which prevents the liquid phase from

passing due to its hydrophobic properties [60]. The process can be visualized in a schematic diagram that represents the DCMD system, Figure 2.13 shows the flow and phase change mechanisms involved. In the MD process, there may be remnants left on the membrane, which can result in fouling. These residues often consist of valuable minerals, including lithium and other important elements, that can be extracted and separated. This dual functionality positions membrane distillation as a promising method for not only purifying saline water but also focusing on the recovery of valuable minerals. At the same time, it addresses the challenge of membrane fouling, making it an attractive option for mineral extraction alongside water treatment processes [8].

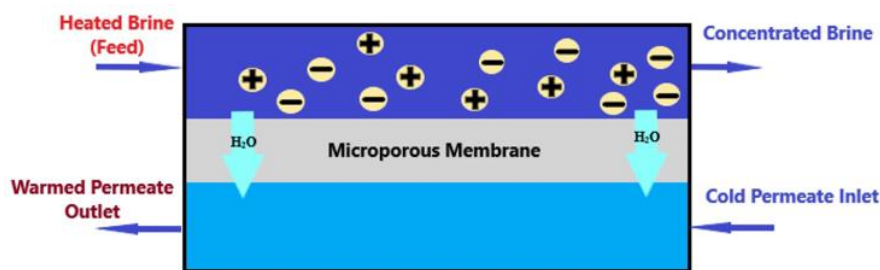


Figure 2.13: Schematic representation of DCMD [8].

Electrodialysis (ED) and its variant, Electrodialysis Reversal (EDR), represent innovative membrane-based technologies that leverage electrical voltage to facilitate desalination, particularly of brackish water. These methods capitalize on the selective ion transport properties of semipermeable membranes, which enable the movement of charged particles under the influence of an external electrical voltage gradient [61]. In a typical ED configuration, cation exchange membranes (CEM) and anion exchange membranes (AEM) are arranged alternately between an anode and a cathode. When an electrical voltage is applied, cations are attracted to the negatively charged cathode while anions are drawn toward the positively charged anode [62]. This movement allows for the efficient

separation of freshwater from concentrated brine solutions, exemplifying the core principles of ion migration and membrane function within the electro dialysis framework [62] EDR shares the fundamental electrochemical principles of traditional ED but introduces a unique approach through the periodic reversal of the direct current voltage. This process typically occurs about three to four times per hour, effectively changing the direction of ion transport across the membranes [63]. The periodic inversion of voltage plays a crucial role in addressing challenges commonly associated with desalination, particularly scaling and fouling on the membrane surfaces [64]. Figure 2.14 a & b shows a representative schematic illustration of ED and EDR, respectively.

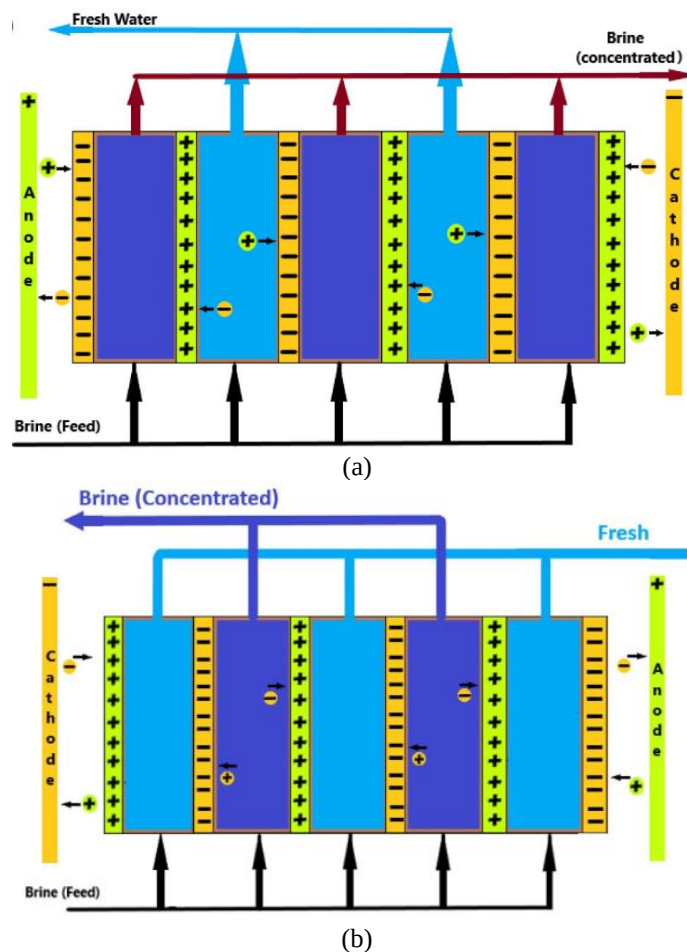


Figure 2.14: (a) Schematic representation of (a) ED [8] and (b) EDR [8].

Reverse osmosis (RO) is a pressure-driven membrane technology commonly employed for desalting saline water [65]. The process involves applying hydraulic pressure to a compartment containing water with a high salt concentration (Figure 2.15). This pressure forces water molecules through a semi-permeable membrane into a compartment with lower salt concentration. To achieve this, the hydraulic pressure should overcome the osmotic pressure difference between the permeate and the concentrated feed solutions. Consequently, the dissolved brine is trapped on one side of the pressurized membrane, while the fresh water passes to the other side [65].

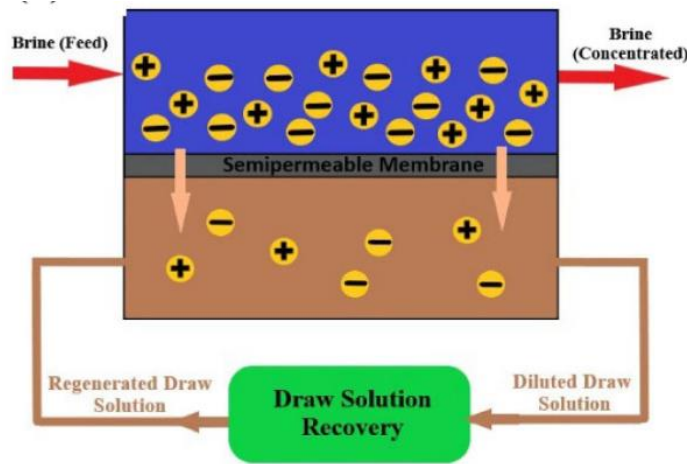


Figure 2.15: Schematic of a typical RO system [8].

(b) Thermal based methods

In the pursuit of freshwater, thermal desalination methods represent crucial advancements in both innovation and efficiency. These techniques utilize thermal energy to heat saline water, causing it to evaporate. The resulting vapor is then condensed into pure water, free from salts and impurities. In addition to water purification, these methods offer potential for mineral recovery from the remaining brine. Unlike membrane-based approaches, thermal desalination relies on the principles of phase change and heat exchange to

effectively convert saline water into drinkable water [8]. The heat required to cause the vapor production can be obtained by several sources such as burning fuels, solar energy etc. One of the most important thermal methods is solar desalination.

Solar desalination harnesses solar energy to produce fresh water from saline sources like brine or brackish water, mimicking the Earth's natural hydrological cycle. This process is rooted in basic principles of physics [66]. The process involves evaporation and condensation, where sunlight heats a cover plate that maximizes light penetration into a basin filled with saline water. Heat transfer through both radiation and convection is vital in this method. The basin, often darkened to enhance absorption, captures the solar radiation effectively, reducing the amount of reflected energy and increasing the efficiency of the desalination process. It represents a specific approach within solar desalination, utilizing sunlight to evaporate water, which subsequently condenses to yield clean, purified water. The simplicity of this process makes it an accessible and sustainable solution for water purification in various environments [67].

The process of solar desalination is effectively mirrored in SS, which are simple to construct and require no moving mechanical components. These systems are not only cost-effective but can also be built using easily accessible and inexpensive materials. In today's world, while there are numerous ways to obtain potable water, many of these methods may prove to be either too costly or difficult to access. Solar desalination offers a standout solution for water purification because of its affordability and reliance solely on solar energy to transform brackish water into clean, drinkable water. Since solar energy is a renewable resource, using it aligns with sustainable and environmentally conscious

practices [68]. The working principle of solar desalination is shown in Figure 2.16. More details about SS and the functionality are given in the next section.

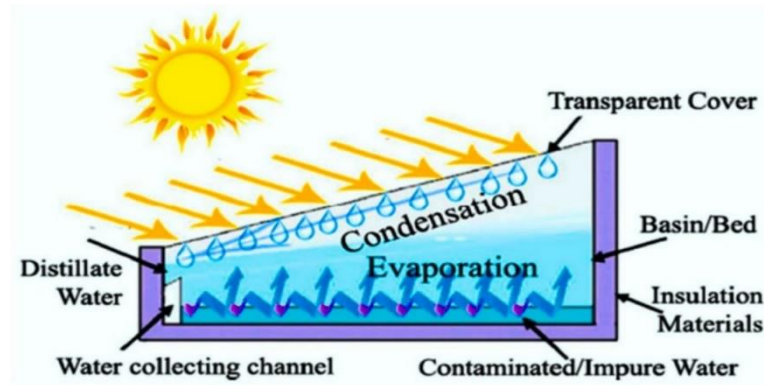


Figure 2.16: Working principle of solar desalination [69].

2.5.2 Active and passive SS

SS can be categorized as passive and active SS. Passive SS rely solely on the solar energy that falls on their surface to operate. The design of a SS typically includes a basin, sealed to be water and air-tight, covered by a slanted glass panel (Figure 2.17). Sunlight passes through this glass panel and heats the saline water in the basin, causing it to evaporate. This process creates a heat-trapping effect within the still, allowing the water to continuously evaporate as it absorbs solar radiation. The evaporated water condenses on the inner surface of the glass panel, leaving behind the salts and impurities. Importantly, no external energy sources are used in this passive system, making it a self-sustaining solution [70].

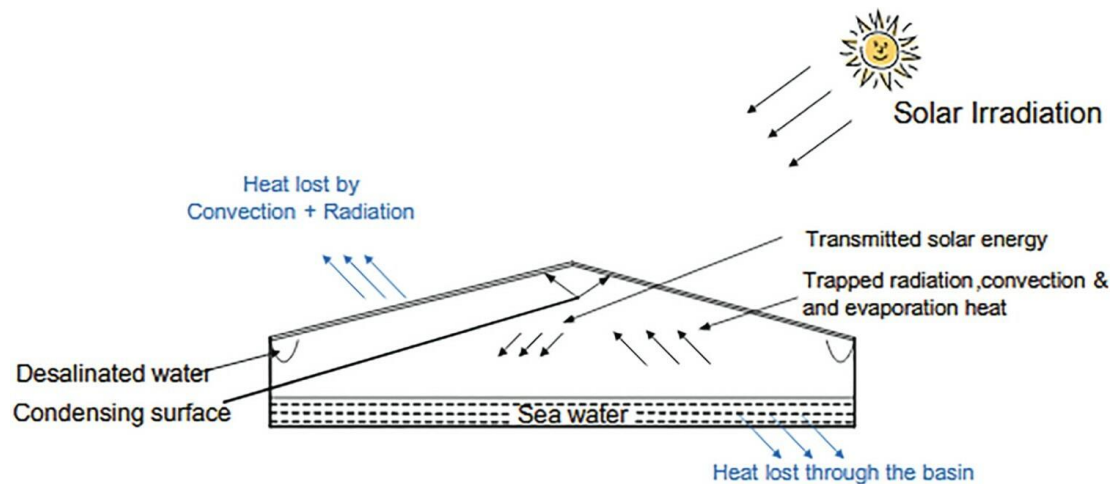


Figure 2.17: Passive double slope SS [71].

On the other hand, active SS incorporate an external heat source to increase the temperature of the saline water, improving the efficiency of the evaporation process. This added heat can come from a variety of sources, such as concentrating solar panels, waste heat, or even a conventional heater. These systems are designed to enhance the natural process of evaporation by increasing the temperature of the water more rapidly than passive systems. Some multistage solar systems also include additional components like a solar radiator and a vacuum pump, which help to further accelerate the evaporation rate and improve overall performance. By utilizing these external heat sources, active SS can produce freshwater more efficiently than passive models [72]. Figure 2.18 shows a schematic of an active SS which uses solar panels to provide the additional heat to the sea water.

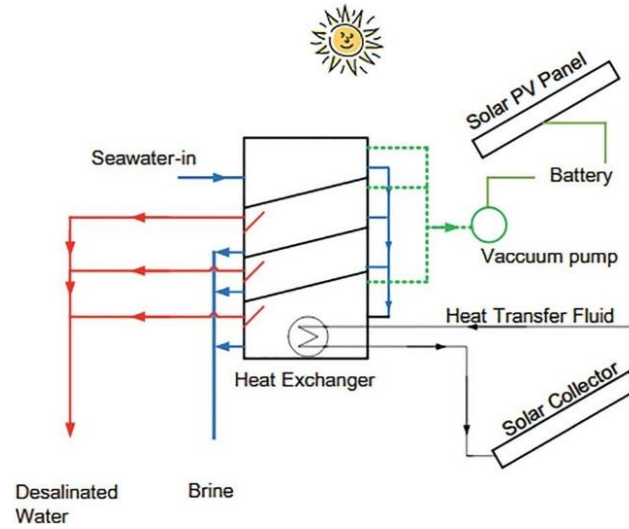


Figure 2.18: Hybrid (PV-T) active SS [71].

2.5.3 Geometric configurations

Analysis of published works shows a variety of SS configurations that are used to provide fresh water. Each design uses solar energy as the main source of energy with varying heating and evaporation mechanisms. It should be noted that out of the many possible configurations, only a few are discussed in this section.

(a) Simple SS (SSS)

Solar radiation penetrates the transparent, V-shaped glass cover of the SSS and is absorbed by the darkened surface at the base of the basin (Figure 2.16). This heat causes the water to evaporate, and the vapor then condenses on the inner surface of the glass. The condensed water is collected and directed into a reservoir through a series of channels. The glass roof acts as a trap for sunlight, preventing it from escaping back into the environment [73]. The design of the SSS encourages effective condensate collection, with the roof plate angled at 10–20 degrees to facilitate water droplets flowing down for collection. On the other hand, a steeper angle hinders the efficient accumulation of condensed water [74].

The SS basin can be constructed from galvanized iron sheets, cement, or fiber-reinforced plastic. Locally, basins can also be built using bricks, sand, and concrete, while industrially manufactured units use refined materials. The roof cover is made from glass or plastic. As water evaporates, the leftover water becomes increasingly concentrated with salts, leading to the formation of a salt layer at the basin's base. Regular flushing is essential to prevent salt precipitation. Adding a fan can increase the evaporation rate without significantly raising power consumption [75]. The inner surface of the still can also be coated with reflective materials to enhance reflection. In seawater desalination, three kilograms of seawater typically produce one kilogram of freshwater, with the remaining brine discharged back into the ocean[76]. The two basic types of simple SS are: single slope stills (SSSS), and double slope SS (DSSS), as depicted in Figure 2.19 a & b, respectively.

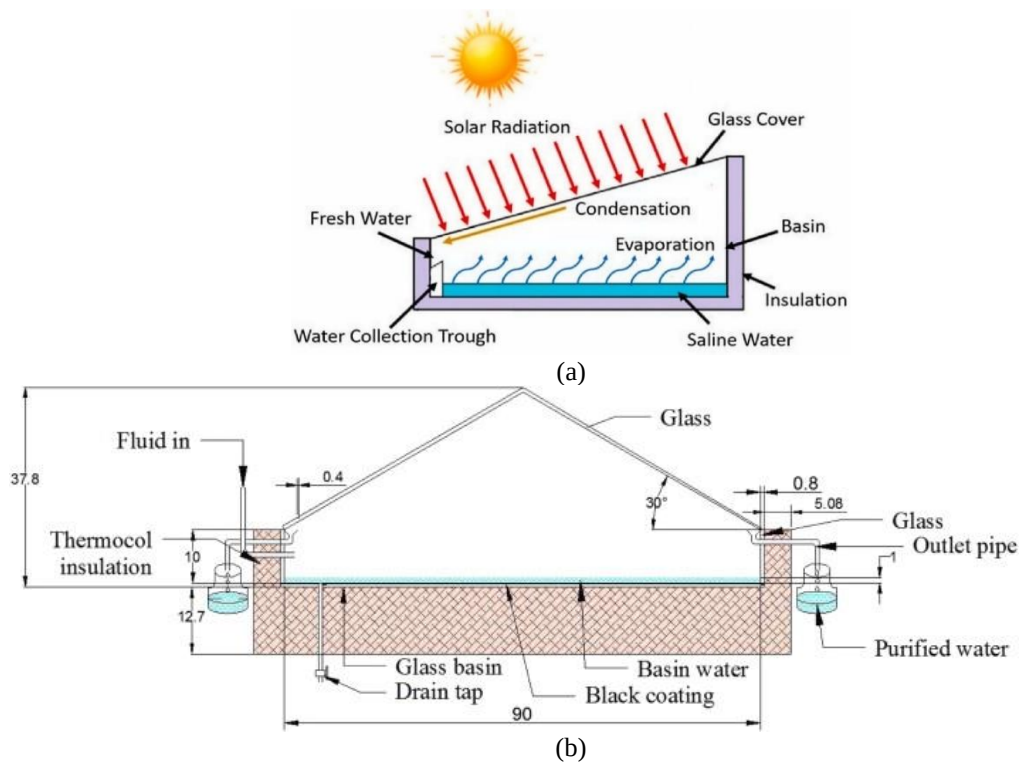


Figure 2.19: (a) Single slope SS [77] and (b) Double slope SS layout [78].

(b) Double-basin SS (DBSS)

In this configuration, solar radiation passes through a tilted glass cover to reach the water in the upper basin. As a result, the water in the upper basin heats up. The evaporated water molecules condense on the inner surface of the toughened glass cover. Due to the slope of the cover, the condensed water flows down and is collected in the gathering trough, eventually reaching the accumulation container [79]. The water in the lower basin is heated by the residual heat from the upper basin water, as well as by the warm water from the discharged tubes as shown in Figure 2.20. The performance of a SS is commonly measured by the amount of water evaporated per unit area of the basin in a day. In this design, heat transfer within the still, from the basin water to the collecting cover, can occur through convection, radiation, and evaporation [80].

The advantage of employing a double basin configuration over a single basin design in SS lies primarily in its ability to significantly increase water output. In a double basin system, solar radiation heats both the upper and lower basins, effectively utilizing more of the incident solar energy compared to a single basin design, where only the water in one basin is heated. The water in the upper basin serves as an additional layer that captures more heat and enhances the overall evaporation process. This dual-layered setup creates a temperature gradient between the upper and lower basins, allowing for the lower basin to be indirectly heated by the condensation from the upper basin, which leads to more efficient heat utilization. As a result, the evaporation rate in the lower basin increases, further boosting the overall water output. Additionally, the double basin configuration optimizes the absorption of solar energy by spreading it across a larger surface area, particularly in areas with high solar radiation. This increased efficiency in harnessing solar energy leads

to higher distillate production without the need for additional energy input, making it a more productive design for water distillation [81].

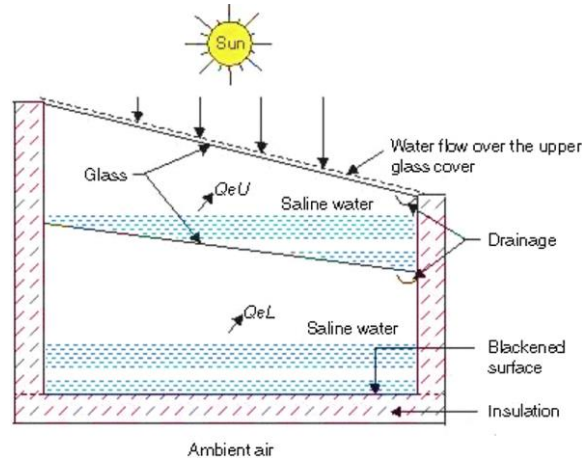


Figure 2.20: Double-basin SS layout [82].

(c) Pyramid SS (PSS)

The PSS as illustrated in Figure 2.21 features a pyramid shaped top cover. This design comes in two main forms: the Triangular Pyramid and the Square Pyramid SS. The key difference between these two types lies in the shape of the basin. In the Triangular PSS, the basin has a triangular shape, whereas the Square PSS utilizes a square-shaped basin. Both configurations share the same basic operating principles but vary in terms of basin geometry [83].

The PSS offers several advantages over the traditional single-slope SS as there is less shading from the side walls. Additionally, for the same basin area, the pyramid shape provides a larger top surface area, which increases the condensation rate due to the larger collection area. The rate of condensation is also enhanced in PSS as one side of the pyramid cover directly receives more intense solar radiation than the opposite side, creating a temperature difference. This contrast between the warmer and cooler sides enhances the

rate of condensation on the cooler side, as the temperature difference between the water surface and the top cover is more pronounced in the pyramid design [84].

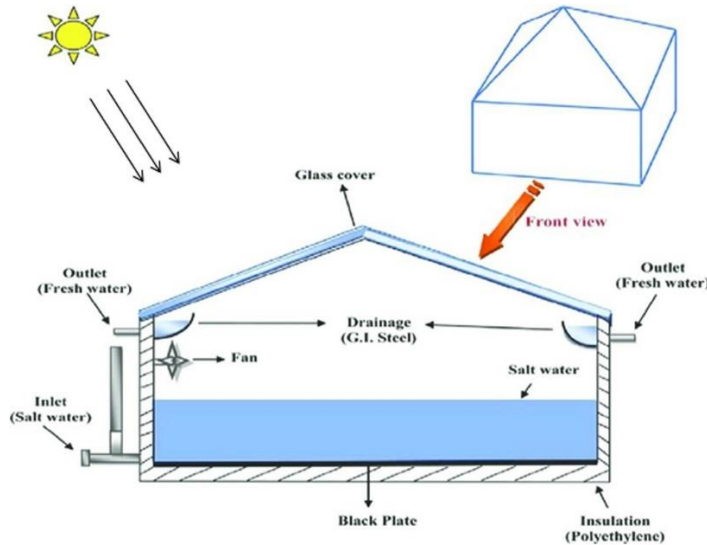


Figure 2.21: Pyramid SS layout [71].

(d) Tubular Solar Still (TSS)

The process of water desalination using the TSS involves the same basic principles as other solar water desalination techniques. As illustrated in Figure 2.22, solar radiation passes through the cover and is predominantly absorbed by the saline water inside the trough. Any remaining heat is absorbed by the trough and the cover. This absorption raises the temperature of the saline water, causing it to evaporate [85]. The water vapor then condenses on the inner surface of the cover, releasing latent heat during the condensation process. Gravity helps the condensed water to flow down the cover's surface, where it is collected in the reservoir [86].

One of the primary benefits of the TSS is the circular design of the transparent tube, which allows the TSS to collect solar radiation from all directions, enhancing the total solar energy it can capture. This improves the overall energy collection in contrast to the SSS,

which typically collects sunlight from one direction only. The cylindrical enclosure of the TSS also eliminates the need for additional thermal insulation, as its shape naturally helps retain heat within the system, leading to increased internal heat accumulation. Additionally, the tubular geometry of the TSS makes it easier to operate under vacuum conditions, improving its efficiency in specific settings. However, the cylindrical enclosure reduces the available space for the evaporator, which limits the evaporation capacity of the device. As a result, the overall evaporation rate may be lower than traditional designs. To mitigate this limitation, incorporating solar concentrators with the TSS can significantly improve its performance. Furthermore, the compact design of the evaporator trough restricts the amount of heat storage material that can be placed inside, which poses a challenge for storing sufficient thermal energy. A potential solution to this issue is the use of external heat storage systems, which could supplement the limited internal space and enhance the system's overall effectiveness in retaining and utilizing heat [87].

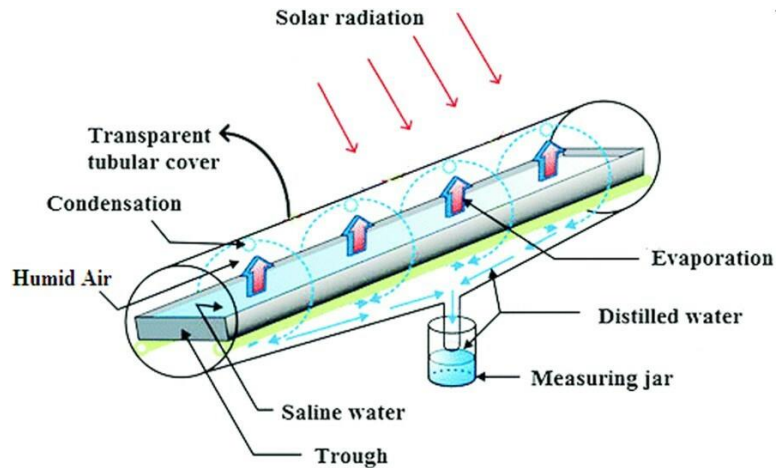


Figure 2.22: Tubular SS layout [88].

(e) Hemispherical SS (HSS)

The distillation system in a HSS is designed in a hemispherical shape, as depicted in Figure 2.23. When solar energy strikes the absorber plate or container, the water inside begins to evaporate, converting into vapor. Due to lower pressure, this vapor rises and comes into contact with the inner surface of the glass dome. Since the temperature inside the glass dome is lower, the vapor condenses back into liquid water. Once the temperature falls below the dew point, condensation initiates, forming water droplets that can be collected [89].

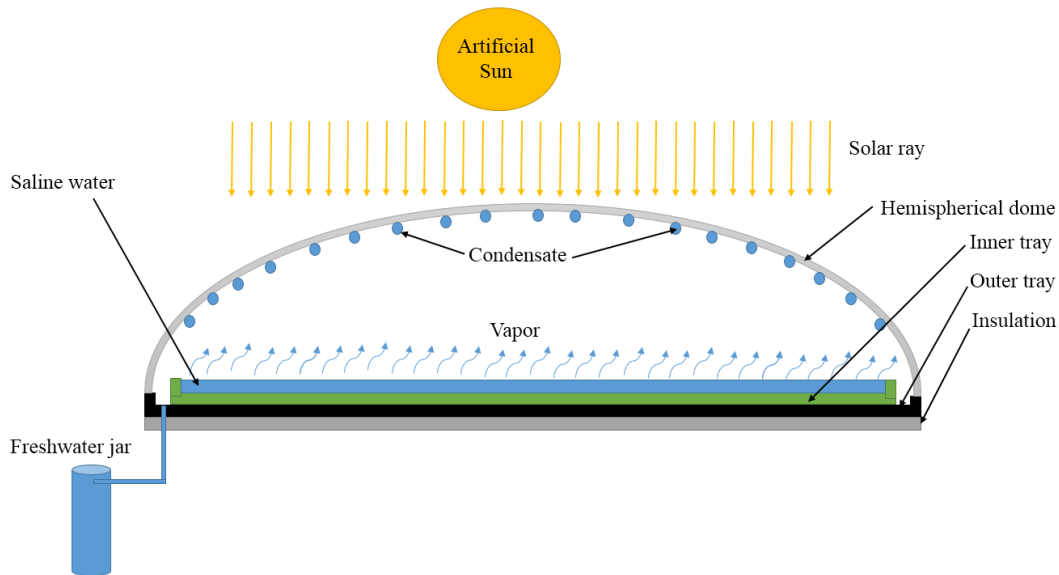


Figure 2.23: Hemispherical SS layout [90].

(f) V-type SS (VSS)

In VSS, solar radiation passes through the glass cover and is largely absorbed by the basin, leading to an increase in temperature. A portion of the absorbed energy is transferred to the basin through convection. The evaporated water then releases its latent heat of condensation on the surface of the glass cover. As condensation forms, the water flows down and is collected by a trough [91]. Figure 2.24 illustrates this setup in detail.

One of the key advantages of the VSS design is its reduced trickling distance compared to conventional SSSS of the same size. In VSS configuration, the distance that the condensed water droplets travel to reach the collection trough is halved. This shorter trickle path allows for quicker collection of condensed water, minimizing the chances of re-evaporation or loss during the process. As a result, the VSS type SS can improve water collection efficiency while maintaining a more compact design than its single slope counterpart [92].

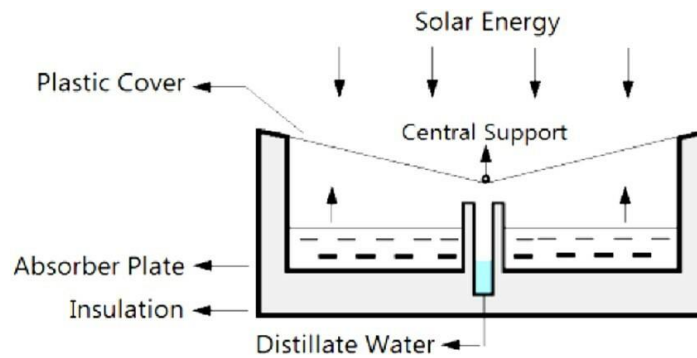


Figure 2.24: V-type SS layout [91].

(g) Spherical SS (SPSS)

SPSS features a shallow, round basin, as depicted in Figure 2.25. The circular basin can be coated to maximize the absorption of incident solar energy. Positioned at the center of a spherical aluminum net, the basin effectively captures sunlight. The solar energy absorbed by the basin heats the saline water contained within, leading to evaporation. As the water vapor rises and condenses on the upper surface of the structure, it trickles down towards the distilled water collection unit [93].

The spherical geometry of SS has been observed to offer several advantages, particularly with its larger condensation surface area. This design allows the still to be oriented in any direction to capture the maximum amount of solar energy which can enhance the water

yield by 32%. This improvement is attributed to the cooling effect on one side of the glass cover, which remains in shadow, further boosting condensation efficiency compared to conventional designs [94].

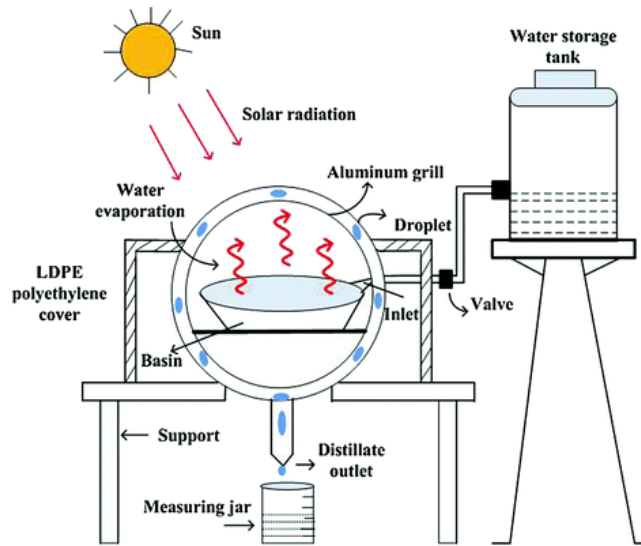


Figure 2.25: Spherical SS layout [95].

(h) Wick-type SS (WSS)

The solar radiation that hits the glass cover transfers heat to the wick surface. A portion of this heat is utilized to warm the water, causing it to flow across the wick through capillary action. A substantial amount of heat is trapped inside the still, allowing energy to move from the wick surface to the glass cover and into the surrounding environment [96]. As the water travels over the wick, it becomes heated and evaporates into vapor. This vapor then condenses on the underside of the glass cover, where the cooler surface facilitates condensation. The condensed water droplets flow downward due to gravity and are collected in the channel [97]. The detailed structure of this system is illustrated in Figure 2.26.

A slanted WSS design allows for higher temperatures compared to conventional types. However, despite its efficiency, its use in practical applications faces several challenges due to the cost required for specialized mounting structures and insulation. Regular cleaning of the fabric wick is also required to remove the accumulated dust. Moreover, maintaining an operable covering layer is crucial, as the dark wick material requires frequent replacement due to degradation from sun exposure. Lastly, the slanted feature in the WSS provides little benefit except in high-latitude regions where its angle becomes more relevant [98].

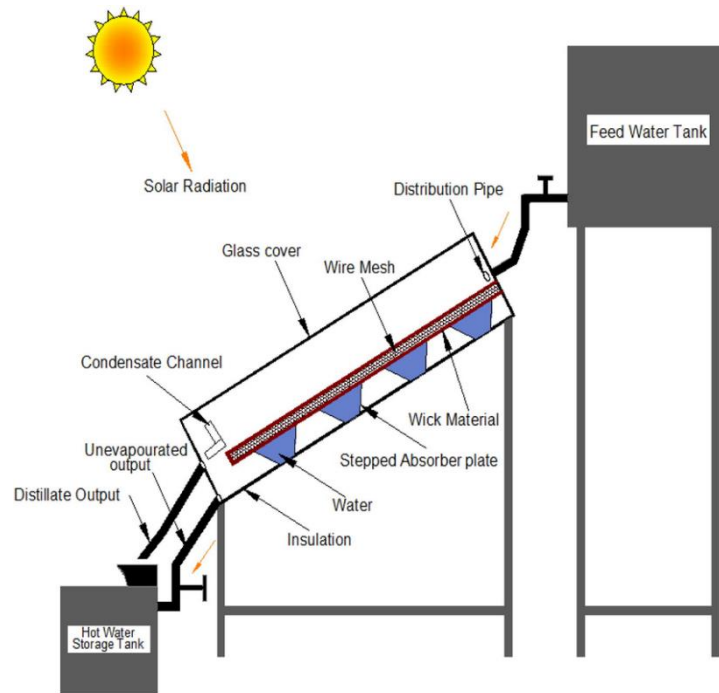


Figure 2.26: Wick-type SS layout [99].

(i) Concentrating collector still (CCS)

The basic operating principle of CCS (Figure 2.27) involves the use of solar concentrators to focus sunlight onto a smaller surface area, thus heating the saline water to much higher temperatures than the direct incident rays alone [100]. The main components of these

collectors include various types such as fixed reflectors with moving receivers, compound parabolic collectors, Fresnel lenses, parabolic troughs, fixed receivers with moving reflectors, and central receivers [98].

By concentrating the solar energy, CCS systems enhance the heat transfer rate and amplify the solar radiation. This heightened temperature makes the CCS more efficient than other still designs as it enables faster evaporation of the saline water, with the vapor then transported to a separate chamber where it condenses into fresh water (approximately 0.5–0.6 gallons of potable water per day per square foot of the reflector area) [99]. However, the construction and maintenance costs associated with CCS are considerably high, and their efficiency is heavily dependent on consistent, direct sunlight. Moreover, their delicate components require careful handling, making them less practical for widespread use in certain settings [101].

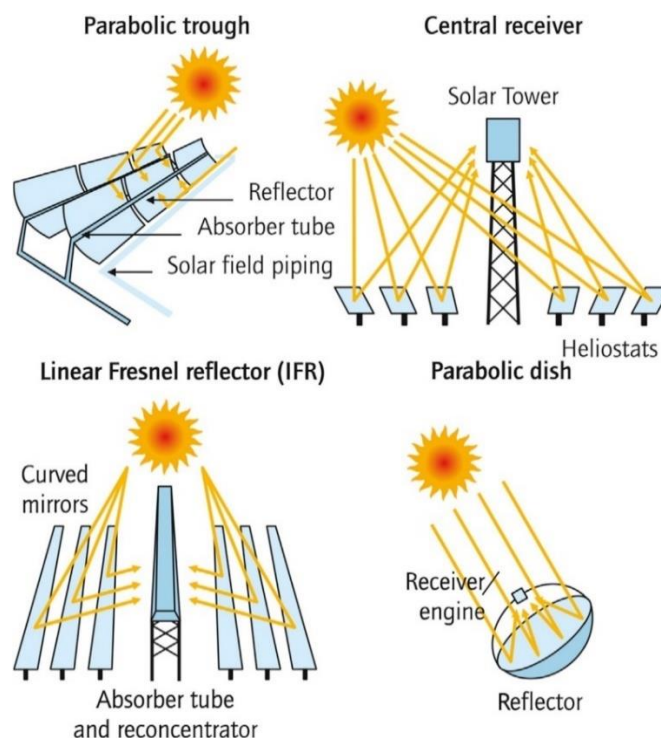


Figure 2.27: Concentrating collector still layouts [102].

2.5.4 Effect of design parameters on SS performance

The thermal performance of SS is influenced by climatic, design, and operational parameters. Climatic factors encompass elements such as solar intensity, wind speed, and ambient air temperature. On the other hand, design factors include parameters such as the basin area, the size of evaporative and exposure surfaces, the inclination angle of the glazing cover, the geometric proportion of the SS, its orientation, the materials used in construction, and the type and thickness of insulation. These factors are crucial in determining the overall efficiency of the system. Operational factors include the temperature differential between the basin water and the glass, the glass temperature itself, the incorporation of hybrid technologies, the application of vacuum systems, heat storage capabilities, and the basin water's temperature. Unlike climatic factors, both design and operational parameters can be effectively controlled to optimize the SS's efficiency. Figure 2.28 provides a detailed overview of the numerous elements and their influence on the SS performance. More details are provided in the following sections.

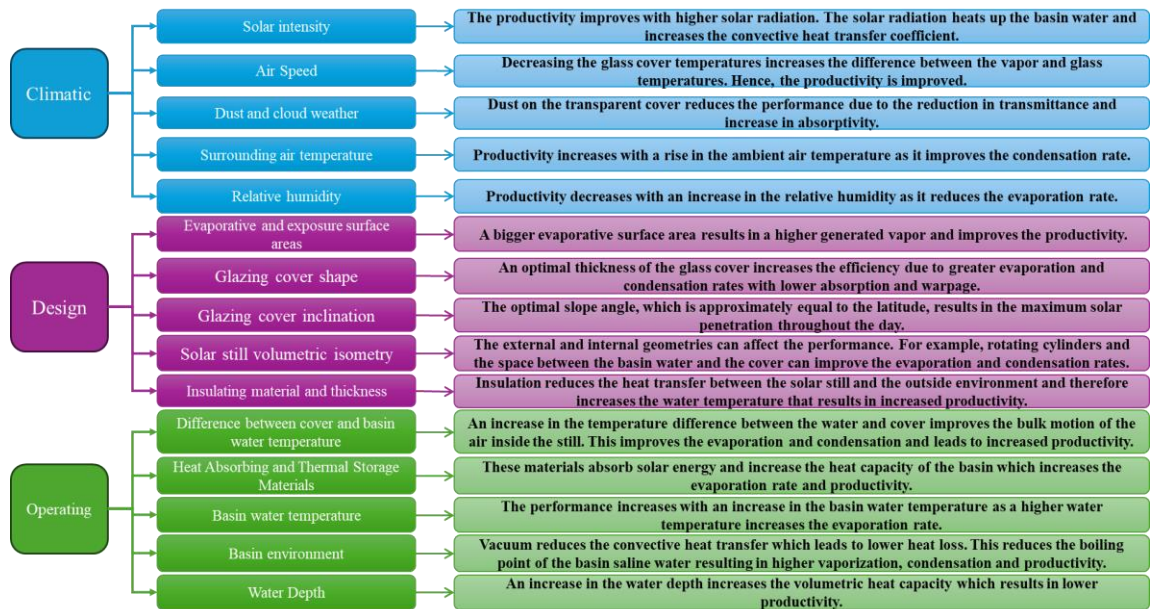


Figure 2.28: Factors that affect the performance of SS.

(a) Solar radiation

As reported in numerous publications, the yield of SS tends to increase with a rise in solar radiation (Figure 2.28). Research consistently highlights that solar intensity is the most influential factor in enhancing SS performance [103]. Nafeya et al. [104] conducted a study on the effect of variations in solar radiation on the SS efficiency. Their findings indicated that a reduction in solar intensity leads to a lower distiller efficiency, while an increase in solar intensity improves it. The most pronounced effect of this was observed in the summer season (Figure 2.29a) [104]. Similarly, Almuhanha [105] observed a direct relationship between the solar radiation and distiller productivity, reporting that higher levels of solar radiation result in greater productivity. Additionally, it was shown that the external parameters such as solar radiation increase the productivity of SS [106], [107], [108] (Figure 2.29b). Higher solar radiation increases the convective heat transfer coefficient inside the basin and the evaporation [109]. In a SS, energy transfer involves the supply of heat for water evaporation in the basin which is then removed at the cover during condensation [110]. Therefore, the productivity of SS improves with increased energy transfer rates [111].

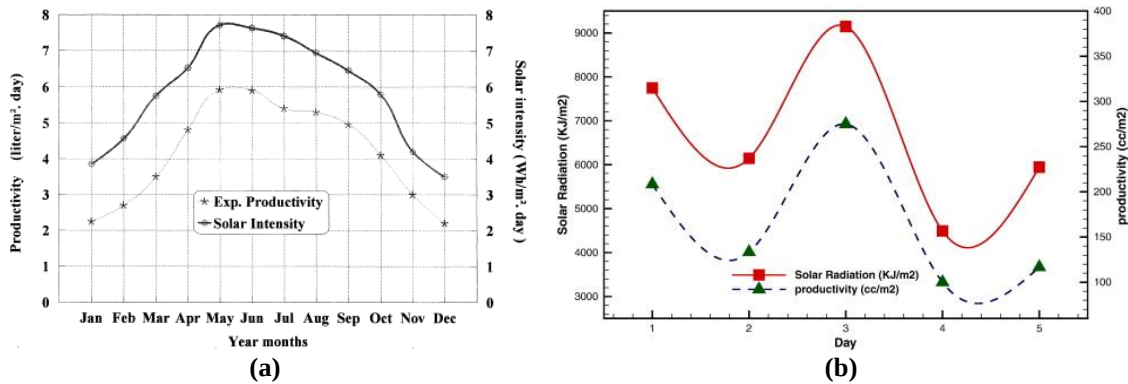


Figure 2.29: (a) Variation of solar radiation and SS productivity [104] and (b) Variation of daily productivity and solar radiation [108].

(b) Ambient temperature

Many studies have explored the impact of ambient temperature on SS performance (Figure 2.28). Theoretical observations show that every 10°C increase in ambient temperature leads to an 8% increase in the SS production [112] (Figure 2.30a). Malik et al. [113] also conducted a similar study and observed that raising the air temperature by 5°C could result in a modest increase in distiller yield (Figure 2.30b). Furthermore, Alheefi [114] examined the effect of ambient temperature on the SS production and showed that the air temperature can affect the performance and productivity of SS.

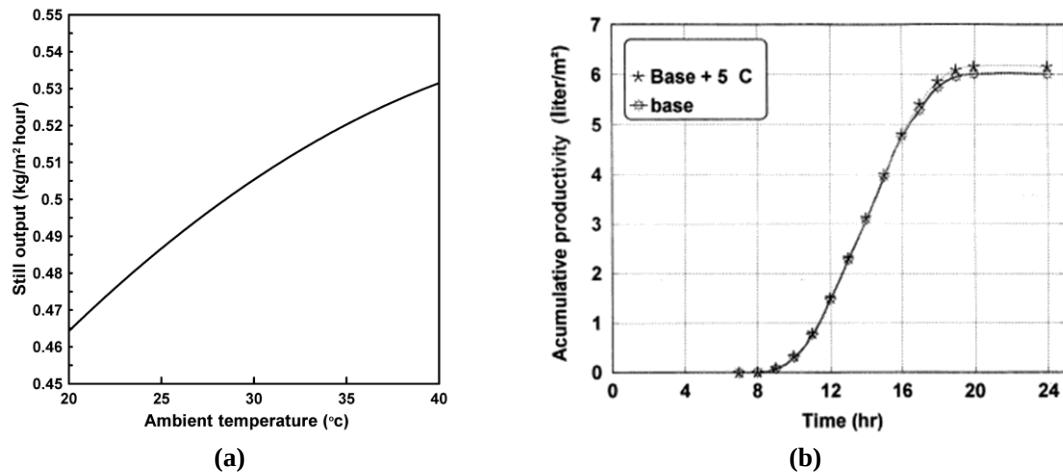


Figure 2.30: (a) Influence of ambient temperature on single distiller output [112] and (b) Effect of air temperature on the total productivity of the distiller [113].

(c) Relative humidity

Change in relative humidity has also been shown to impact the performance of SS (Figure 2.28). Koffi et al. [115] studied the effect of humidity variations, (between 40% to 65%) on still performance (Figure 2.31). Their findings indicate that an increase in relative humidity correlates with a reduction in SS output. This relationship underscores the importance of considering humidity levels when evaluating and optimizing SS productivity [116]. Moreover, Mohsenzadeh et al. [117] highlighted that decreasing the relative

humidity and the aspect ratio of the evaporation chamber increases the temperature difference significantly between the cover and the water in the basin. This temperature gradient is essential for improving the evaporation and condensation processes within the SS.

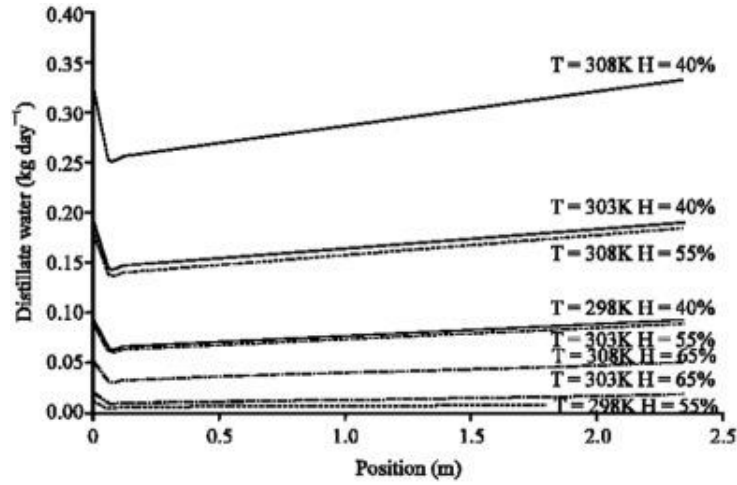


Figure 2.31: Effect of humidity on SS productivity [115].

(d) Wind velocity

The effect of wind velocity has been confirmed by numerous publications [118] (Figure 2.28). It is well-known that the yield of a SS improves as the glass cover temperature decreases [119]. Drop in cover temperature causes an increase in the temperature difference between the water and the cover which leads to an increase in water production due to higher condensation [111]. Results from active and passive SS also confirmed that higher air speeds boost distiller productivity [120], [121]. The influence of wind speed on SS productivity is depicted in Figure 2.32a.

However, SS productivity may decrease if the air speed increases beyond a certain critical limit as showing in Figure 2.32a [121]. Results showed an increase in productivity with an increase in wind speed followed by a reduction in water production (up to 13%) at higher

wind speeds [124]. Increasing the wind speed also affects the heat transfer coefficients in SS as the higher wind speeds reduce the cover temperature (Figure 2.32b) [122]. Additionally, the water-to-glass radiative heat transfer coefficient and glass-to-sky radiative heat transfer coefficient decreases with increasing air speed while the water-to-glass evaporative heat transfer coefficient remains unaffected [122].

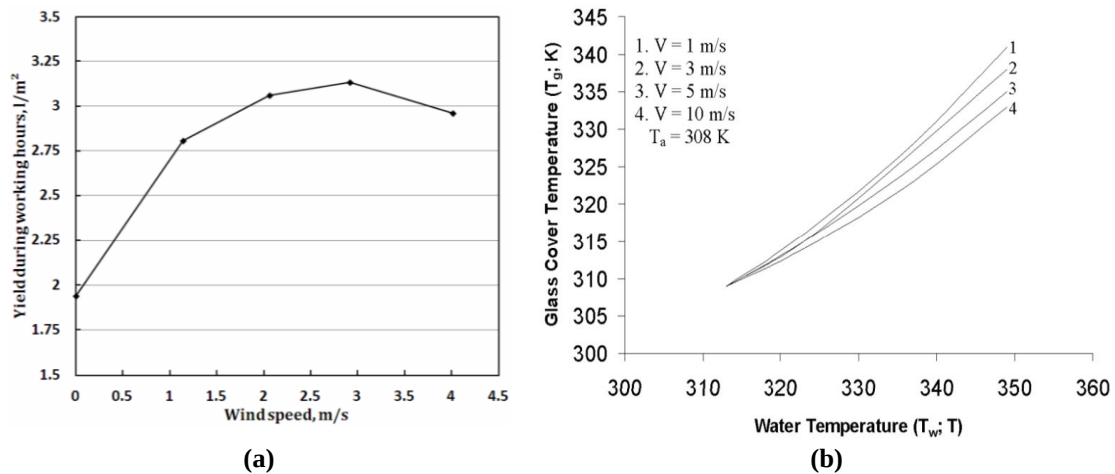


Figure 2.32: (a) Change in yield of SS vs wind speed [121]. (b) Effect of air speed on glass cover temperature [122] .

(e) Water depth

The level of water has been identified as an important parameter that affects the production of SS [123] (Figure 2.28). Experimental results conducted at different water levels show that higher water levels result in low productivity resulting in an inverse relationship between the water level and water productivity [124], [125], [126] (Figure 2.33a). Moreover, as a level of water increases, it results in an increase in volume and volumetric heat capacity. This lowers the water temperature for the same solar radiation resulting in lower vapor and water output [116], [127].

As the solar radiation decreases during evening and night times, the heat stored in higher water levels is released. This allows for continuous evaporation at night [128]. In a separate study [129], it confirmed that the production of a double SS basin increased with a reduction in water levels. Similar studies from other authors also resulted in similar results where the optimized productivity typically falls between 2 cm and 6 cm [130], [131] (Figure 2.33b).

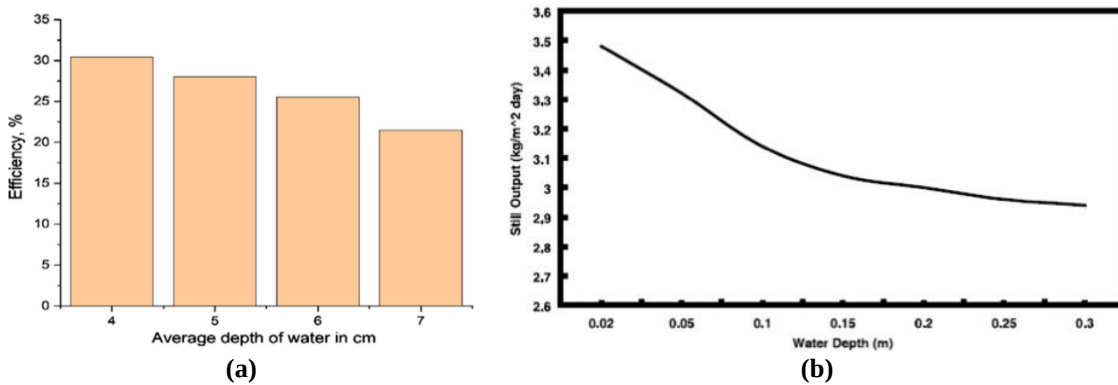


Figure 2.33: (a) Daily efficiency with basin depth [126]. (b) Effect of water depth on the output [112].

(f) Geographical location

Geographical location can also affect the SS efficiency. For example, Figure 2.28 shows the effect of dust on SS performance. The absorptivity and transmittance of the glass cover plays a crucial role in the performance of a SS and dust or dirt accumulation can affect the optical properties of the cover [132]. Studies have also shown that dust and dirt buildup reduces glass transmittance [133]. Therefore, areas with heavy dust exhibit lower SS efficiency. Hottel and Woertz [134] examined the effect of dust accumulation on glass covers and reported a reduction of approximately 1% due to the presence of dust and dirt. Similarly, El-Nashar [135] investigated the effect of dust accumulation on evacuated-tube collectors and reported a glass cover transmittance drop of 10%. Furthermore, neglecting

to clean the solar collector system can lead to a 70% reduction in the glass cover's transmittance [136].

Moreover, Jafari et al. [137] conducted a study across various cities to determine the optimal locations for installing SS. Their findings revealed a direct relationship between solar radiation and freshwater production. Therefore, cities with higher temperatures and greater solar exposure resulted in higher yields. Conversely, higher relative humidity and wind resulted in a lower SS efficiency. Therefore, they concluded that hot, arid cities with high solar radiation, low wind speeds, and high-water tariffs are ideal locations for SS installations (Figure 2.34).

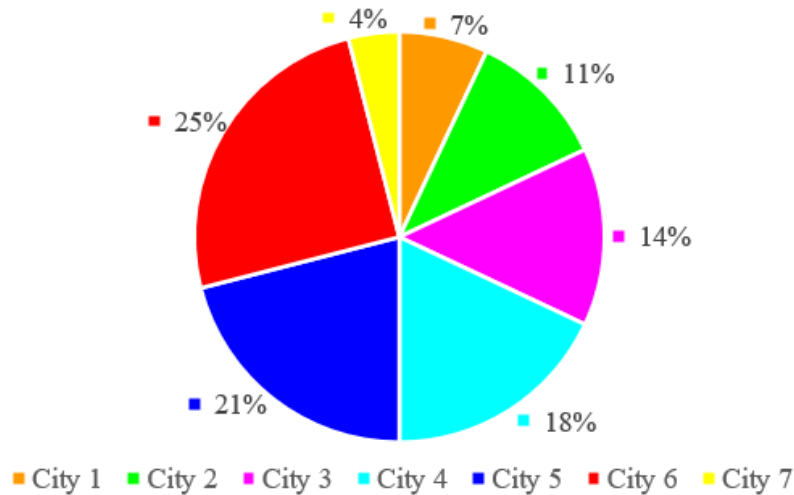


Figure 2.34: Relative annual freshwater production for various cities (adopted from [137]).

(g) Evaporative and exposure surface areas

The primary principle of SS revolves around the evaporation of water in the basin under the influence of solar energy. The incident sunlight heats the water, causing it to vaporize, and the resulting vapor then condenses on the inner surface of the glass cover. This process transforms saline or contaminated water into clean, drinkable water. A key parameter in

this mechanism is the evaporative surface area, which refers to the portion of basin water directly exposed to solar radiation. A larger evaporative surface area increases the water's exposure to sunlight, leading to greater vapor generation. As a result, expanding the evaporative surface area directly contributes to improved vapor production and higher overall efficiency of the SS system (Figure 2.28).

This can be accomplished in many ways. For example, installing corrugated and finned basin liners inside a SS can improve the basin or evaporative surface area. Omara et al. [138] explored the effect of surface modifications on the SS performance. They modified the basin liner design, by introducing corrugations and fins. Their results demonstrated that the freshwater output rose by 21% with corrugated absorbers and 40% with finned absorbers (Figure 2.35a). Sakthivel et al. [139] also investigated the effect of incorporating jute fabric within the basin to increase the exposure surface area to solar radiation (Figure 2.35b). Their findings indicated a 20% improvement in productivity and an 8% rise in efficiency. Similarly, Velmurugan et al. [140] demonstrated that combining fins and sponges can enhance the performance of the SS. The results revealed that this dual approach increased the distiller's productivity by an impressive 80%, showcasing the potential of such modifications in boosting the overall efficiency of SS systems.

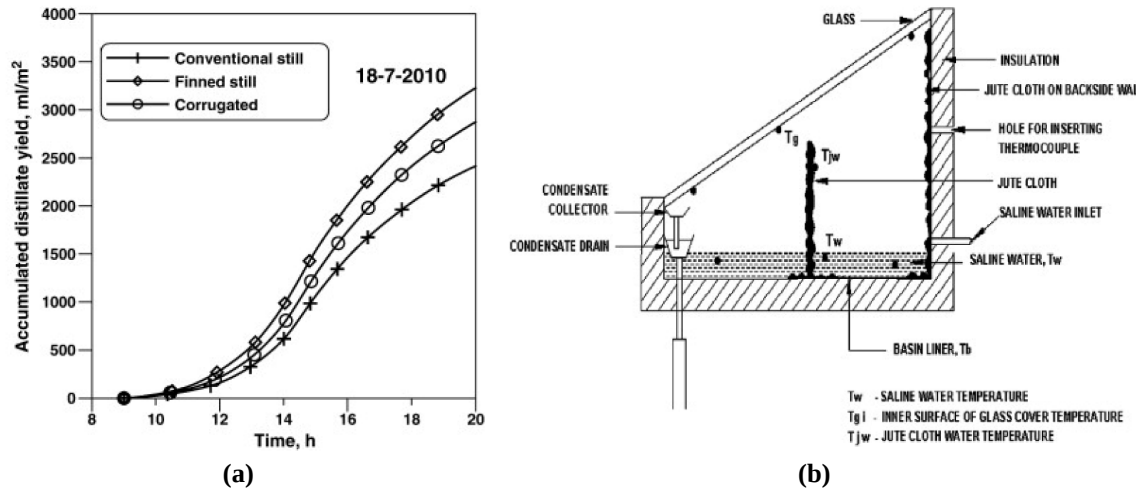


Figure 2.35: (a) Accumulated SS distillate with finned and corrugated absorbers [138]. (b) Single slope SS with vertical jute [139].

(h) Glazing cover thickness and inclination

As widely recognized, the glass cover serves as the primary gateway for solar radiation to reach the water in the SS basin (Figure 2.28). Consequently, researchers have studied various properties of glass that influence the performance of SS. These properties include its thickness and angle of inclination. The key role of glass in SS systems is to permit high-energy solar radiation to enter while preventing longer wavelengths from escaping. This design ensures that the distiller captures and retains the maximum amount of solar energy without allowing it to radiate out. The glass cover's external surface is exposed to the ambient environment, which helps keep its temperature relatively low. Simultaneously, the inner surface of the glass comes into direct contact with the vapor generated above the basin water. This configuration allows the inner glass surface to act as a condensation site for the vapor since it maintains a lower temperature than the surrounding vapor [141].

Research indicates that a glass thickness between 3~4 mm is considered optimal for SS. Ghoneyem and Ileri [141] evaluated glass thicknesses ranging from 3 mm to 6 mm and

concluded that the 3 mm thickness yielded superior evaporation and condensation rates compared to the thicker options. This finding underscores the importance of glass thickness in maximizing the efficiency of SS systems.

On another hand, the glass cover inclination angle plays a significant role in influencing the thermal performance of SS. The glass inclination angle dictates the overall surface area of the cover, which in turn affects the heat transfer processes inside the distiller. The glass inclination angle also facilitates the collection of the condensed distillate. The slope of the glass determines how efficiently the condensed water droplets are guided toward the collection channel, ensuring optimal water recovery. Furthermore, the speed at which droplets move on the glass surface is directly influenced by the angle. Larger angles result in faster droplet motion, while excessively shallow angles may cause the droplets to slide back into the basin, adversely impacting performance. The inclination of the glass also determines how much direct solar radiation is received by the distiller over the course of a day. An optimized angled glass cover ensures maximum exposure to solar radiation, enhancing the system's efficiency. Additionally, the inclination interacts with seasonal variations, such as the sun's declination angle, which influences the amount of solar radiation absorbed versus reflected. During winter, steeper angles may reduce efficiency due to increased reflection, while in summer, the same inclination might boost performance. These seasonal effects highlight the challenge of determining an optimal year-round inclination angle for the glass cover [111].

Akash et al. [142] explored the effect of inclination angle on the SS performance. Their experiments incorporated angles of 15°, 25°, 35°, 45°, and 55°. The findings revealed that an inclination angle of 35° yielded the highest distillate output and this angle aligned

closely with their location's (latitude of 31°). Therefore, their results indicated a strong correlation between the glass angle and geographic latitude. In addition, Singh and Tiwari [143] supported these findings and concluded that the distiller's output is maximized when the glass cover's inclination matches the latitude of the test location (Figure 2.36).

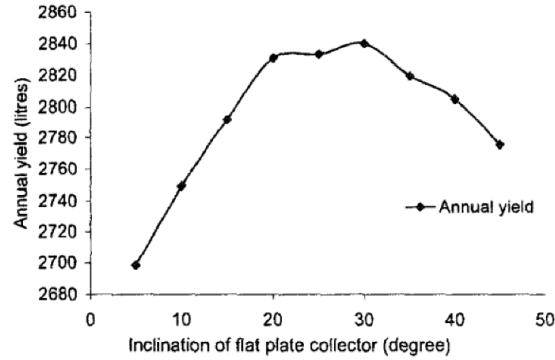


Figure 2.36: Annual productivity with various collector tilts [143].

(i) SS volumetric isometry

The external configuration of a SS also influences its thermal efficiency and overall productivity (Figure 2.28). Recent studies have emphasized the importance of both the external and internal design to enhance the device's performance. Factors such as the distance between the water surface in the basin and the inner surface of the glass glazing also play a critical role in determining the freshwater output. Innovative designs, such as the rotating disc SS incorporate two rotating discs within the distiller to enhance the water evaporation [118]. The highest productivity was achieved using a corrugated disc equipped with a wick (Figure 2.37). Under these optimized conditions, the distiller demonstrated an 124% increase in productivity compared to a conventional SS. This groundbreaking design underscores the potential of creative internal modifications to maximize the efficiency of solar desalination systems.

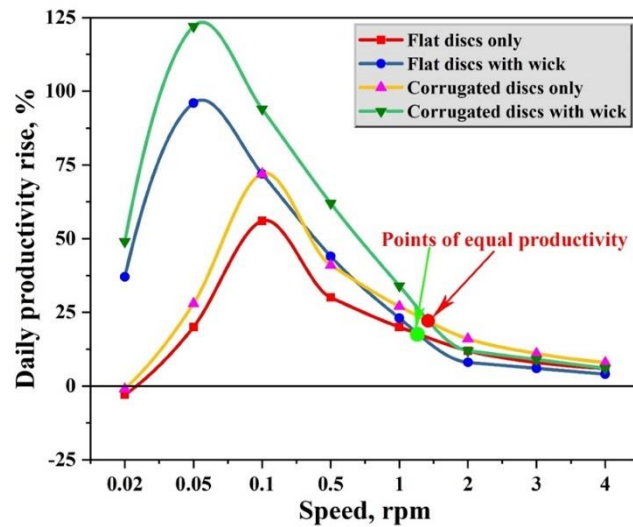


Figure 2.37: Effect of disc speed and shape on SS productivity [118].

(j) Insulating material and thickness

The effectiveness of a SS largely hinges on minimizing heat loss from the basin to the surrounding environment (Figure 2.28). To achieve this, insulating the distiller's basin becomes crucial, as it ensures that the thermal energy is utilized effectively. This highlights the significance of selecting the right type and thickness of insulation materials. Research has demonstrated that proper insulation can enhance the performance of SS significantly, with improvements ranging from 7% [144] to as much as 180% [145]. A variety of insulation materials have been explored in studies, including wood [146], sawdust [147], thermocol [148], fiberglass [149], gypsum [153], and Styrofoam [150]. The key criterion for choosing an insulation material is its low thermal conductivity, which would prevent heat transfer to the surrounding air. Additionally, the thickness of the insulation layer is critical and is determined based on the material's thermal conductivity to optimize thermal resistance. By carefully considering these factors, the efficiency of SS can be improved substantially [72], [150].

Sahoo et al. [148] demonstrated an 11% improvement in SS efficiency by incorporating thermocol as an insulation material. This highlights the potential of lightweight and cost-effective materials in enhancing thermal performance. Meanwhile, Ford et al. [151] explored the impact of various insulation properties on SS productivity. They concluded that composites made of cement, gypsum, and expanded polystyrene offered excellent thermal isolation and were effective for such applications.

In a related study, Khalifa and Hamood [150] examined the effect of insulation thickness on SS performance. They used Styrofoam, with a density of 35 kg/m^3 and a thermal conductivity of $0.029 \text{ W/m}\cdot^\circ\text{C}$, to insulate their setup. Their findings revealed a significant increase in productivity, rising from $1.81 \text{ L/m}^2\cdot\text{day}$ without insulation to $3.28 \text{ L/m}^2\cdot\text{day}$ with a 60 mm thick Styrofoam sheet (Figure 2.38). Moreover, they derived a mathematical equation to establish a direct relationship between insulation thickness and distiller productivity.

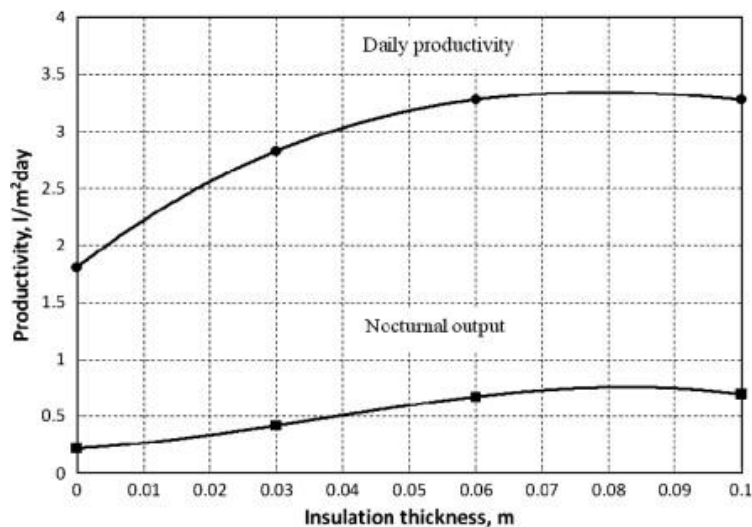


Figure 2.38: The variation in distiller productivity with different insulation thicknesses [150].

(k) Basin water temperature

Raising the temperature of the basin water has a direct and substantial impact on the efficiency of SS systems. To ease the vaporization process in a SS, researchers have explored the use of additional solar energy to elevate the water temperature in the basin. This approach leverages the abundance and sustainability of solar power as an efficient heat source [152]. These systems increase the water temperature by concentrating the sunlight onto specific areas, typically targeting the saline water either before it enters the distiller or directly in the basin. Consequently, a higher temperature enhances the vapor generation, leading to greater freshwater output. By accelerating the rate of evaporation, the overall productivity of the distiller can be improved (Figure 2.28).

Hiroshi [152] implemented internal and external reflectors to amplify the amount of solar energy directed toward the basin water (Figure 2.39a). This addition resulted in a notable rise in the basin water temperature and boosted the evaporation rate. The authors also discussed the tilt angle of the external mirror for optimal performance.

Similarly, Eltawil and Omara [153] integrated the SS with a variety of components, including a flat plate solar collector, a spraying unit, an external condenser, and a solar air collector, to achieve higher basin water temperatures. Their findings revealed that the output of the developed SS (DSS) outperformed that of the conventional SS (CSS), especially when the solar collector was incorporated, as demonstrated in Figure 2.39b. They observed an increase in SS productivity ranging from 51% to 148%.

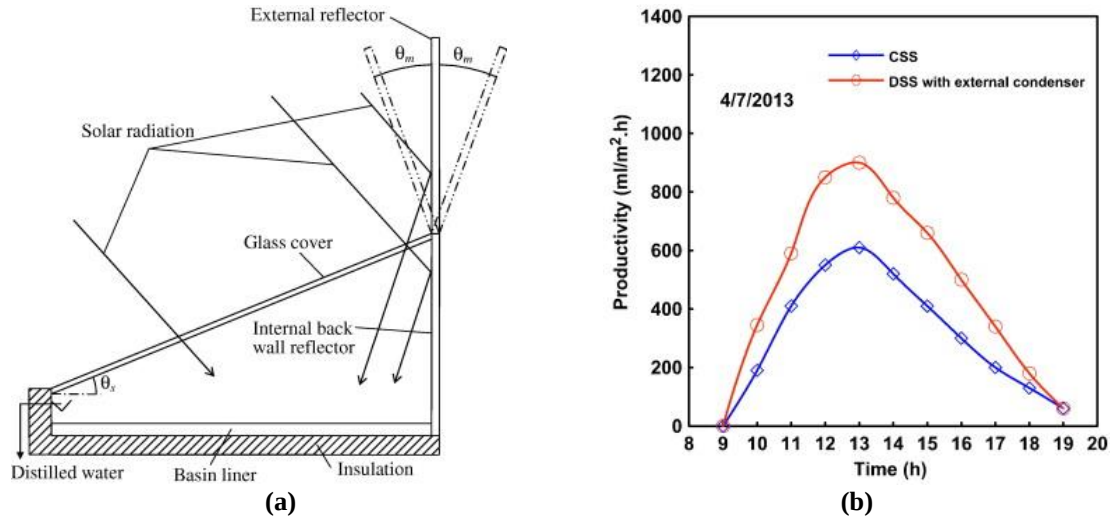


Figure 2.39: (a) Single slope SS with internal and external reflectors [152], (b) Differences in hourly productivity for CSS and DSS in hybrid SS system [153].

(I) Basin environment

Numerous studies have explored the impact of operating SS under vacuum. The primary purpose of creating a vacuum inside the distiller is to eliminate the heat transfer via convection. This ensures any possible heat loss could occur only through evaporation and radiation. Moreover, introducing a vacuum minimizes the presence of non-condensable gases, which may impede the condensation process (Figure 2.28).

Panchal [154] observed a significant improvement (56%) in freshwater production with vacuum tubes (Figure 2.40a). Ahmed et al. [155] explored the influence of creating a vacuum within a multistage evacuated SS. Their investigation revealed that applying vacuum conditions had a substantial impact on the distillation process. The authors observed that both the overall daily output and the yield from individual stages improved significantly with an increase in vacuum levels inside the system (Figure 2.40b).

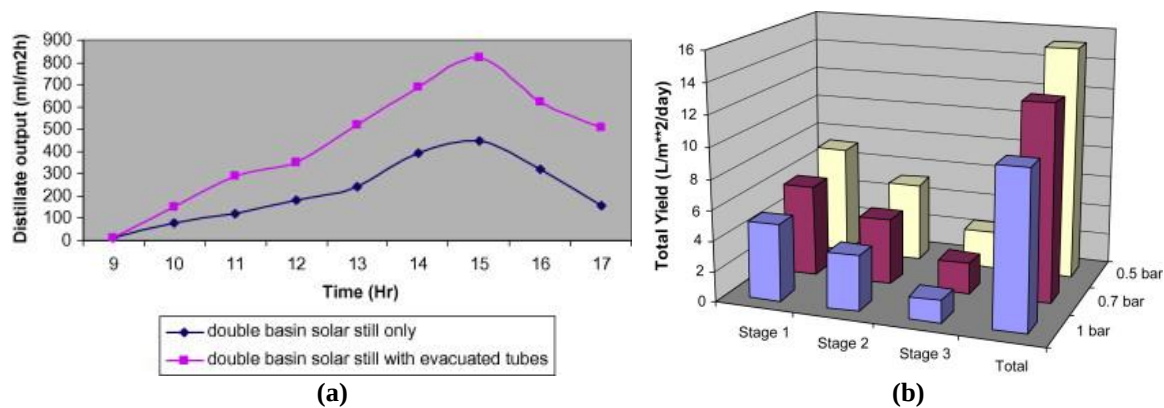


Figure 2.40: (a) The hourly distillate of the SS with vacuum tubes [154]. (b) Daily yield of total and individual stages under vacuum [155].

(m) Difference between the cover and basin water temperature

Researchers have identified the difference between cover and water temperature as a significant factor in SS efficiency (Figure 2.28). However, this is not a direct factor as it is affected by several other factors such as wind speed, water depth etc. Patel and Kumar [156] examined the efficiency of a double-slope SS under varying water depths and air velocities. Their research demonstrated that increasing wind speed, cooling the glass covers, and reducing water depth significantly enhanced the distiller's yield. They attributed this improvement to a greater temperature difference between the water and the glass. Abu-Arabi et al. [157] validated these findings by confirming that lowering the glass temperature through cooling measures boosts SS performance.

Similarly, Janarthanan et al. [158] employed flowing water over the glass surface to reduce its temperature. This technique effectively increased the temperature difference between the water and glass, resulting in a substantial rise in productivity. Murugavel et al. [159] also highlighted that the SS productivity depends on the temperature gradient between the water and the cover. Also, the findings indicated that cotton cloth demonstrated superior performance in terms of water yield (Figure 2.41a). Moreover, Srithar [160] confirmed that

maximizing the temperature gradient between the water and the cover can be used in enhancing the freshwater output of SS (Figure 2.41b).

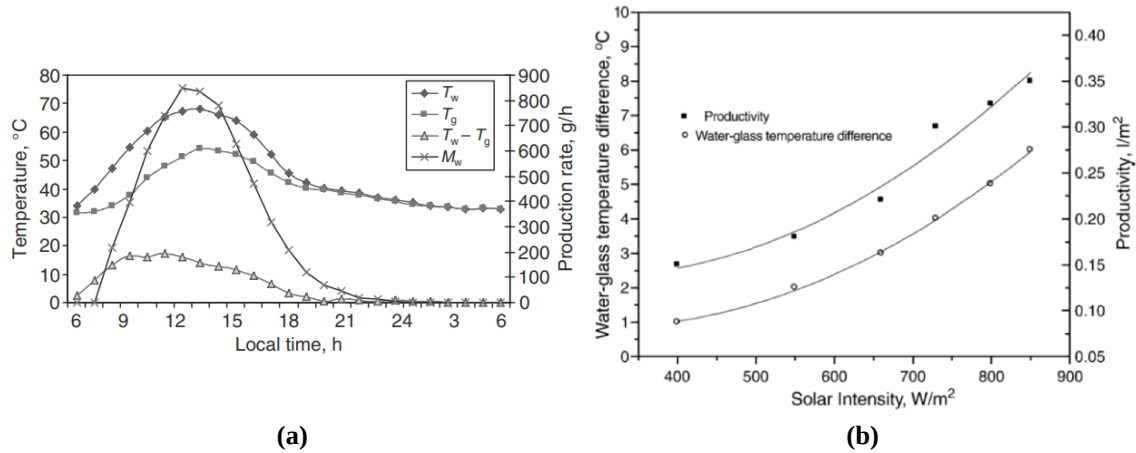


Figure 2.41: (a) SS temperature and productivity with time [159]. (b) Impact of solar intensity and water-cover temperature difference on SS productivity [160].

(n) Thermal storage and heat absorbing materials

The main limitation of SS lies in the relatively low output of distilled water per unit area, which can render them inefficient or unsuitable for certain applications. As a result, there is significant potential to enhance the performance of these systems [161]. Numerous studies have reviewed different types of distillation systems, as well as solar thermal collectors and their applications. It has been established that the efficiency of SS is influenced primarily by factors such as the intensity of solar radiation, the duration of sunshine, and the design of the still [162], [163]. These materials store energy which makes them highly efficient [164]. Phase Change Materials (PCMs) also store heat and offer a high energy storage density compared to other methods [165]. The role of absorbent materials and PCM is crucial when it comes to enhancing the performance of SS. One effective method to improve the efficiency of a still is through the incorporation of materials that can increase the (a) absorption and (b) storage of solar radiation.

The idea of adding external materials to SS dates to earlier studies, where researchers experimented with various dyes to improve the still performance [166]. For instance, some researchers investigated the impact of using coal and charcoal as absorbents as they boosted the thermal efficiency of the SS [109]. The incorporation of heat absorbing and thermal storage materials into SS is a well-established method to improve their performance. Enhancing the absorptivity of the absorber liner increases the ability of the SS to capture solar radiation and transfer heat to the basin water and increase the heat capacity of the basin which increases the evaporation (Figure 2.28). As discussed previously, a larger temperature difference between the basin water and the cover significantly boosts SS efficiency. To achieve higher water temperatures or maintain elevated temperatures for extended periods, especially during cloudy or nighttime conditions, researchers have introduced various heat absorbing and storage materials into the basin water. These materials include gravels, a mix of violet and black dyes, charcoal, and black wires. The effectiveness of these materials has been shown to improve further with increased water depth in the basin [167]. These materials function by capturing and storing solar energy, thereby increasing the basin's heat capacity. This, in turn, leads to higher evaporation rates and greater productivity (Table 2.2) [168].

Table 2.2: Effect different absorber materials on SS productivity [168].

No#	Name of Absorbent Materials	Increase daily productivity (%)
1	Dyes	10% ~ 19.8%
2	Dark green dyes (50 mg/l and 100 mg/l)	(14.8%) and (12%)
3	Red carmoisine (50 mg/l and 100 mg/l)	(7.4%) and (19.9%)
4	Black naphthylamine (50 mg/l and 172.5 mg/l)	(15.9%) and (17 ~ 28.8%)
5	Soot powder	13% ~ 17%
6	Charcoal	15% more than wick-type stills and 11% ~ 18% more than black-paint and 23% ~ 92% more than blackened rock-bed
7	Rubber material	38%
8	Black dye	60%
9	Black ink	45%
10	Absorbing black-rubber mat	38%
12	Baffle suspended absorber	20%
13	Black gravel	19%
14	Potassium dichromate	26%
15	Sponges and fins in a stepped still	96%
16	Sponge cubes	14% ~ 18%
17	Black granite gravel	17% ~ 20%

Abdallah et al. [161] investigated to evaluate the impact of incorporating absorbing materials, such as coated and uncoated porous media known as metallic wiry sponges and black volcanic rocks, as absorber liners in SS. Their study demonstrated that all these materials enhanced the performance of SS compared to conventional designs. The results revealed that among the tested materials, black rocks yielded the most significant water collection, followed closely by the coated metallic wiry sponges (Figure 2.42a). The productivity of the modified SS increased by 60% for black rocks, 43% for uncoated sponges, and 28% for coated sponges, respectively (Figure 2.42b). Moreover, Jamal et al. [169] investigated the effect of dissolved salts, such as copper sulphate, potassium permanganate, potassium dichromate, cobalt chloride, and tetramethyl-para-phenylenediamine (TPMD) has also been investigated to enhance the efficiency of SS.

Further research examined the influence of various black-paint absorber materials on the thermal performance of solar desalination units [170]. Several other materials have also been investigated. For example, Akash et al. [171] studied using a black rubber mat increased daily water production by 38%, while black ink enhanced it by 45%. The most effective material was black dye, which boosted productivity by around 60%. More recent experiments involved placing blocks of different sizes in the basin of the still with upto 273% improvement [185]. Researchers have also explored the use of solid materials for energy storage in SS processes. They investigated the incorporation of black gravel and charcoal particles as a storage medium within a SS. Their findings indicated that both materials were effective in enhancing the performance of the SS. The charcoal particles, with their high absorptivity, helped improve the efficiency by capturing and retaining more energy [167], [172].

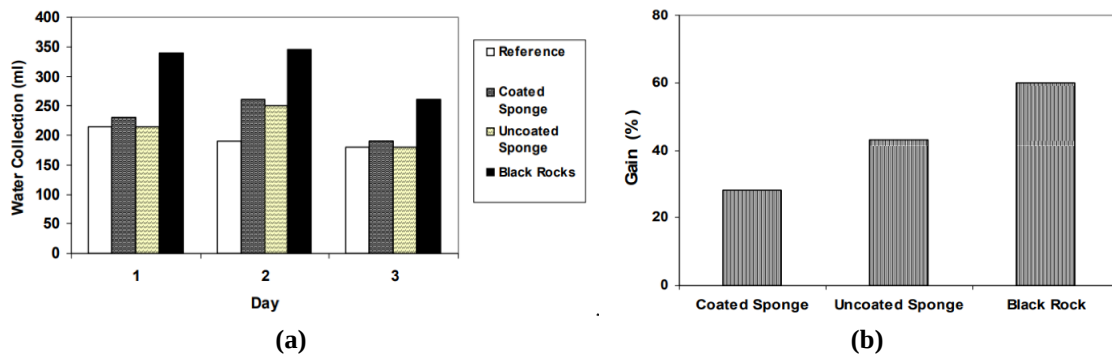


Figure 2.42: (a) SS with total water production with/without porous materials over three days. (b) Productivity increase with different absorbing materials [161].

Similar to absorbing materials, PCMs have emerged as a promising solution for thermal energy storage, thanks to their high energy density, minimal volume change, and availability across a wide range of temperatures [173]. These materials store energy in the form of latent heat, which is absorbed or released during phase transitions, making them highly efficient for capturing and retaining heat [164]. PCMs have the advantage of storing

significant amounts of heat within narrow temperature ranges, offering a high energy storage density compared to other heat storage methods [165].

In contrast to latent heat storage, the specific heat capacity of sensible heat storage materials is much lower, often requiring up to 100 times more material to store the same amount of energy. This makes sensible heat storage less practical for high-temperature energy storage applications. Additionally, during the discharge process, sensible heat storage suffers from a reduction in storage medium temperature, which causes the temperature of the heat transfer fluid to decrease. This drop in temperature can impact the efficiency of systems like SS, especially in colder conditions [174].

One of the main benefits of PCMs for SS is their ability to mitigate these challenges. By storing heat during the day and releasing it through the phase change process at night or on cloudy days, PCMs ensure a more consistent energy supply. As the temperature drops, the system efficiency is maintained as the stored latent heat is released during the transition from liquid to solid [175].

PCMs can be categorized into solid-solid and solid-liquid types, with most existing PCMs falling into the latter category [176]. For SS applications, choosing a cost-effective PCM is key to ensuring both economic feasibility and operational efficiency [177]. The ideal PCM should possess various favorable properties, including minimal volume change during phase transitions, good phase equilibrium, high density, and low vapor pressure. Additionally, PCMs should exhibit chemical stability, compatibility with construction materials, and safety features such as being non-toxic and non-flammable, while also being

affordable and recyclable. These properties make PCMs an effective solution for enhancing the performance of SS [178]. Figure 2.43 provides a general classification of PCMs.

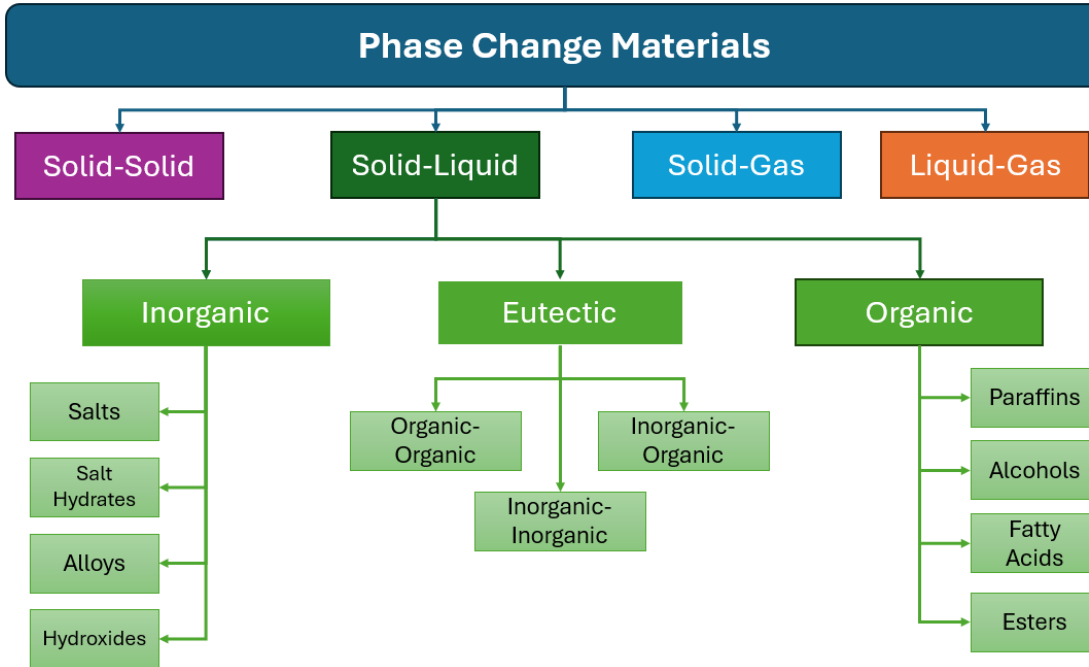


Figure 2.43: General classification of PCMs [177].

Several studies have been conducted to enhance the efficiency of solar desalination systems by incorporating PCMs. The use of PCMs such as paraffin wax has been shown to increase the productivity of solar desalination systems[179]. Research on organic PCMs suggests a more environmentally compatible option, which not only offers ecological benefits but also increases the water productivity[180]. The use of PCMs has also been explored in improving the efficiency of SS as they reduce the potential for leakage and minimize the surface contact resistance. The effect of finned-encapsulated PCM reported a 44% improvement in water production [181].

Nanoparticles have also been shown to significantly improve the thermal conductivity of solar desalination systems, leading to enhanced performance. For example, incorporating

silver (Ag) nanoparticles into paraffin wax revealed a remarkable 112% increase in productivity due to the higher thermal conductivity provided by the nanoparticles [182]. Similarly, nano- Co_3O_4 and aluminum shavings demonstrated a reduced melting time by approximately 50 minutes, while also leading to a 24% increase in cumulative water production [183]. In another study, the use of copper oxide (CuO) nanoparticles combined with paraffin wax resulted in a 113% improvement in water productivity [184].

2.5.5 Review of relevant studies

Conventional and non-conventional SS provide a sustainable solution for addressing water scarcity by utilizing solar energy to purify saline or brackish water. Researchers have explored various methods and materials to enhance the efficiency and productivity of SS. Most studies have focused on conventional fabrication techniques and materials to improve the thermal performance, evaporation rates, and durability. However, these traditional approaches often lack the precision, versatility, and scalability offered by modern manufacturing technologies such as AM. This research employs AM techniques to design and manufacture enhanced SS devices and a few notable studies that incorporate advanced manufacturing techniques and highlight their potential in SS are discussed below.

Koh et al. [9] introduced hydratable plastics made from highly amorphous regenerated cellulose using AM. Their material exhibited interconnected micro and sub-nano water channels that facilitated efficient evaporation of saline water. When incorporated into a solar vaporizer, it achieved a remarkable reduction in salinity levels, exceeding World Health Organization standards for potable water.

Cao et al. [10] employed FDM to fabricate tree inspired, cone-shaped 3D Janus evaporators designed for efficient solar desalination. These evaporators achieved 99.80% solar absorption by combining a porous inner hydrophobic acrylonitrile-styrene-acrylate absorber and a capillary driven outer air laid paper layer. The system demonstrated stable performance over 14 days.

Kaviti et al. [11] combined anodization with 3D printing to create micro-hierarchical and nano-hierarchical structures on aluminum plates. These pyramid shaped patterns achieved an evaporation efficiency of 60% for saline water in controlled experiments. Their findings highlight the impact of surface morphologies and AM potential on evaporation efficiency.

Sun et al. [185] developed a high-performance solar still featuring a truncated FDM PLA conical evaporator. Their design aimed to maximize water evaporation efficiency of approximately 95%. Similarly, Chaule et al. [186] introduced a 3D-printed solar evaporator using polypyrene filament. Their design demonstrated a solar energy utilization up to 99%.

Li et al. [187] developed a 3D-printed porous solar evaporator composed of graphene oxide (GO), sodium alginate (SA), and carbon nanotubes (CNT), designed to exhibit low thermal conductivity. The device achieved high performance in solar steam generation and efficient solar absorption exceeding 97%.

Wang et al. [188] designed a 3D-printed bionic solar evaporator using Projection Micro Stereolithography (PuSL) technology. The innovative structure enabled a water evaporation rate of $4.12 \text{ kg m}^{-2} \text{ h}^{-1}$ with a solar thermal efficiency of 92.1%.

Venkateshwaran et al. [189] developed a FDM PLA 3D-printed sine-grooved solar evaporator. The study investigated the effect of varying water depths (100, 150, and 200

ml) on evaporation performance, recording evaporation rates of 30%, 20%, and 17.5% respectively.

While these studies showcase the promise of AM in advancing SS technology, this research builds upon this foundation by further exploring the effect of AM-enabled surface design improvements to enhance the performance of SS. By leveraging AM's precision and adaptability, this study aims to contribute to the development of cost-effective, scalable, and high-performance solar desalination systems.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 Materials & manufacturing

In this work, the performance of AM SS was explored with different cover materials and base geometries. The influence of substrate geometry on the desalination efficiency was investigated by comparing three morphologically distinct PLA bases (flat, V-shaped, and sinusoidal). Several parameters were also studied for the base material such as XRD, FTIR, TGA, and DSC. The SS experiments were also conducted with two distinct cover materials: (1) glass and (2) acrylic. Critical cover properties influencing the SS performance were analyzed, including optical transmittance and contact angle.

The single-slope SS apparatus (Figure 3.1) with varying cover and basin geometries was designed using computer-aided design (CAD) software (SolidWorks®). A 15.5 cm (length) × 15.5 cm (width) × 9.5 cm (height) SS was manufactured. A 10 cm x 10 cm x 1 cm 3D-printed PLA platforms (layer thickness: 0.2 mm, infill density: 50%) were printed (flat, V-shaped, and sinusoidal). FDM PLA AM was employed to manufacture the SS base.

Two transparent covers were tested: (i) 3 mm glass and (ii) 6 mm acrylic with the same bases (flat, V-shaped, and sinusoidal). The cover were inclined at 17.24° to achieve the maximum solar transmission. Acrylic sheets (5 mm thickness) were used to form the structural framework of the SS. Several apertures were used to collect and supply fresh and saline water. Thermocouples were also installed to measure the cover and water temperature.

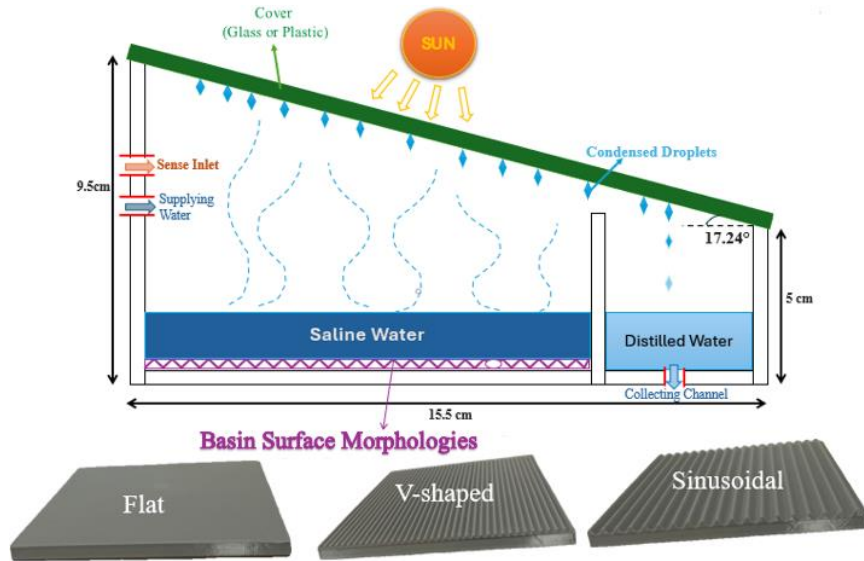


Figure 3.1: Schematic of SS and FDM PLA bases.

The PLA bases for the SS were fabricated using a Creality Ender-5 S1 3D printer (Figure 3.2), which employs FDM AM technique. All bases were fabricated with a nozzle size of 0.4 mm and a bed temperature of 75°C to optimize the interlayer adhesion. The print speed was maintained at 80 mm/s, while a rectilinear infill pattern at 50% density was selected to ensure structural rigidity while minimizing material consumption.



Figure 3.2: Creality Ender-5 S1 machine.

3.2 Experiment setup and instrumentation

The experimental trials were performed during winter (March 2025) at the King Fahd University of Petroleum & Minerals (KFUPM) in Dhahran, Saudi Arabia. Separate experiments were conducted to study the effect of cover and base for various water depths. Two SSs with different covers, flat base, and 100 mL of saline water were tested to study the effect of cover. The SS were positioned to ensure uniform exposure to solar irradiance (Figure 3.3a).

In the second phase, three SS units were constructed, each incorporating a distinct basin geometry (flat, V-shaped, and sinusoidal) as shown in Figure 3.3b. These variations were designed to evaluate the effect of surface morphology on SS performance. To ensure consistency across trials, all three stills were fitted with identical transparent acrylic covers. Three different water levels (100 mL, 150 mL, and 200 mL) were employed to study the effect of water depth on SS performance. During all experiments, the SS were placed under similar environmental conditions, ensuring equal exposure to sunlight and ambient temperatures to ensure identical meteorological conditions during testing.

The experimental trials spanned from 07:00 to 16:00 local time, encompassing peak solar irradiance (11:00–12:00) and the subsequent decline in solar radiation until sunset. Thermal data, including cover surface temperature (°C) and water temperature (°C), were logged at 30-minute intervals using calibrated K-type thermocouples (LUTRON BTM-4208SD digital thermometer; accuracy: $\pm 0.4^{\circ}\text{C}$). Environmental parameters were monitored using an automated meteorological station (Rika Sensor RK900-01). The system recorded wind speed (± 0.1 m/s accuracy; range: 0–45 m/s), and ambient temperature ($\pm 0.5^{\circ}\text{C}$ accuracy; range: -40 – 60°C) at 30-minute intervals. Solar Radiation

was quantified using a Pyranometer sensor (Renkeer Model RS-TBQ; spectral range: 0.3~3 μ m) paired with a monitoring host, achieving a resolution of 1 W/m². All devices were connected to a solar charging system with a solar panel, controller, and battery as illustrated in Figure 3.3c. The fresh water was collected and measured to find the hourly production rate.

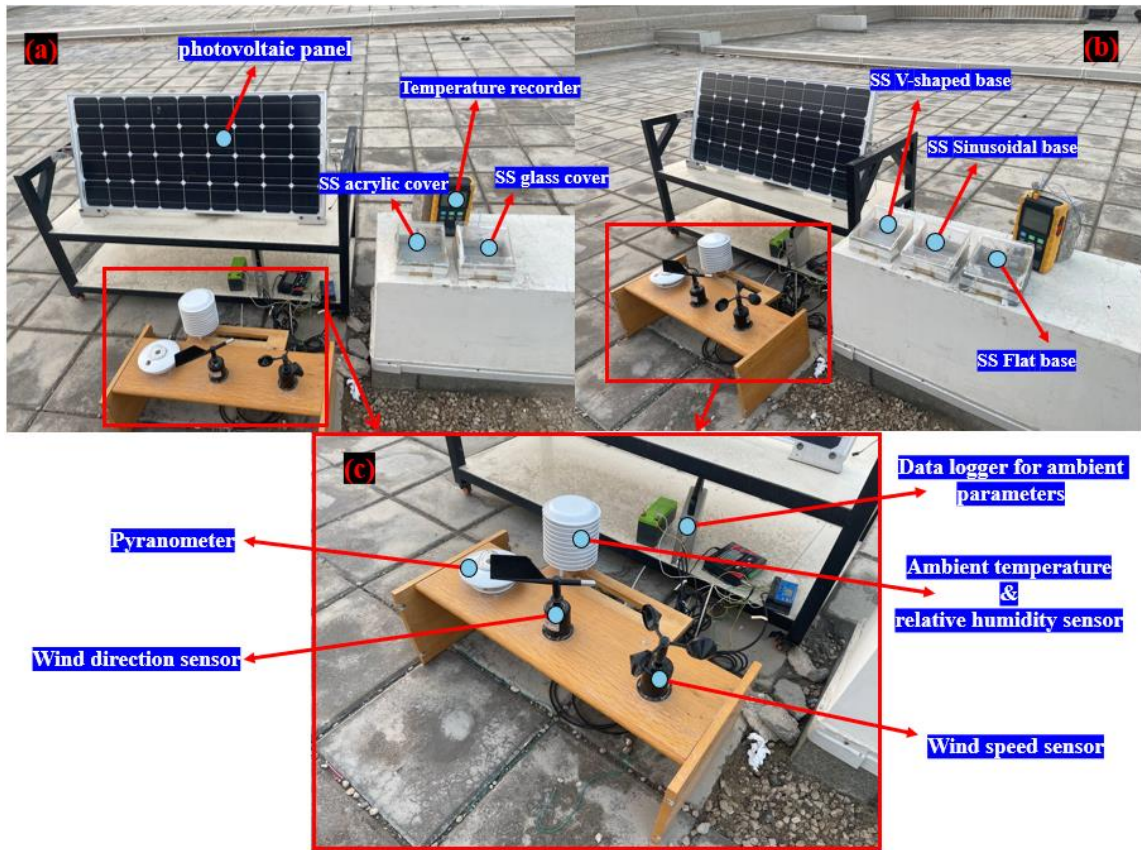


Figure 3.3: Experimental setup employed in this work.

3.3 Surface and material characterization

Various characterization techniques were used to understand the material used for the SS basin. Characterization techniques such as XRD, DSC, TGA, and FTIR were performed on the AM basin surfaces to understand their interaction with solar radiation and water.

Moreover, contact angles and UV-Vis analysis was used to understand the differences between glass and acrylic covers.

3.3.1 X-Ray Diffraction (XRD)

XRD is a non-destructive analytical technique extensively employed for characterizing the microstructural properties of polymeric materials, including amorphous and semi-crystalline systems [190]. This method enables quantitative determination of structural parameters such as lattice constants (via Bragg's Law, $n\lambda = 2d \sin\theta$), crystallographic defects, preferential molecular orientation, and percent crystallinity [190].

The crystallinity and phase composition of the FDM PLA bases were characterized using a Rigaku MiniFlex 600-C XRD (Figure 3.4). Diffraction patterns were acquired across a 2θ angular range of 5° to 70° with a step size of 0.01° . Distinct Bragg reflections corresponding to the semi-crystalline PLA matrix were identified.



Figure 3.4: Rigaku MiniFlex 600-C XRD.

3.3.2 Fourier transform infrared spectroscopy (FTIR)

FTIR is a powerful experimental technique used for identifying various materials, including organic, polymeric, and some inorganic substances [191]. This method provides a detailed understanding of a material's chemical structure and properties by directing infrared light onto a sample and analyzing the resulting absorption or transmission. The unique absorption patterns, known as spectra, correspond to the vibrational modes of the chemical bonds within the material.

FTIR analysis was conducted using a Thermo Scientific Nicolet iS10 spectrometer (Figure 3.5) equipped with an attenuated total reflectance (ATR) accessory featuring a diamond crystal. Spectral data were acquired across a wavenumber range of 600 to 4000 cm^{-1} at a resolution of 4 cm^{-1} with 32 scans per sample to optimize signal-to-noise ratio. The obtained absorbance spectrum was analyzed to identify functional groups and molecular bonding characteristics inherent to the PLA substrate.



Figure 3.5: Thermo Scientific Nicolet iS10 spectrometer.

3.3.3 Thermogravimetric analysis & Differential scanning calorimetry

TGA is used to monitor changes in the mass of a material as it undergoes temperature variations. This method is widely utilized to study thermal stability and composition of

materials [192]. During the TGA analysis, the sample is subjected to a controlled temperature program, either increasing or decreasing over time. The corresponding mass changes are recorded, providing valuable insights into processes such as decomposition, oxidation, and loss of moisture or volatile components. Mass versus temperature data from TGA can be used to determine key thermal properties and reactions.

DSC is employed to analyze thermal transitions in materials as they undergo heating or cooling [193]. This method is instrumental in studying the material response to changes in temperature. The fundamental principle of DSC involves measuring the amount of energy needed to heat a sample at a constant rate. This energy requirement is compared to a reference material under identical conditions, providing insight into the sample's thermal behavior. Phase transitions, melting points, glass transitions, and other critical thermal events in the material can be identified by DSC analysis.

TGA and DSC were performed using a Netzsch STA 449 F3 simultaneous thermal analyzer (Figure 3.6). The samples were heated from ambient temperature to 600°C under an argon atmosphere (50 mL/min flow rate) at a constant heating rate of 10°C/min. Mass loss profiles (TGA) and heat flow curves (DSC) were acquired to quantify decomposition kinetics, glass transition (T_g), crystallization (X_c), and melting (T_m) behaviors. Data acquisition and analysis were conducted using Netzsch Proteus® software.



Figure 3.6: Netzsch STA 449 F3 machine.

3.3.4 Contact angle

The contact angle measurement is widely used to assess the liquid interaction with a solid surface [194]. This measurement provides valuable information about a material's wettability, which is key to applications such as coatings, printing, and biomedical devices. The test determines the angle at which a liquid droplet meets a solid surface, reflecting the balance between adhesive and cohesive forces at the interface. In practical terms, a low contact angle (less than 90°) suggests a hydrophilic surface where the liquid spreads easily. Conversely, a contact angle greater than 90° indicates a hydrophobic surface that resists wetting. Materials with extremely high contact angles ranging from 150° to 180° are termed superhydrophobic.

A Kyowa contact angle goniometer (Japan) was employed to assess the wettability of the samples using the sessile drop method. A water droplet with a volume of $5\ \mu\text{L}$ was dispensed from a height of 10 mm, and the contact angle was measured immediately.

3.3.5 Ultraviolet visible spectroscopy (UV-Vis)

UV-vis spectroscopy is used to analyze the material interaction with ultraviolet and visible light. It works by measuring the amount of light absorbed, transmitted, or reflected by a sample across specific wavelengths [195]. This interaction provides important insights into the material's structure and composition. The intensity of absorption is governed by the Beer-Lambert Law, which connects absorbance with the concentration of the absorbing species, the path length of the light through the sample, and the material's molar absorptivity [196].

Agilent Cary 60 UV-vis machine (Figure 3.) was employed to measure the absorption, reflection, and transmission characteristics of the various covers (Glass and Acrylic) employed in this work. The instrument was set to operate within a wavelength range of 200 to 800 nm. For data processing and analysis, the Cary WinUV© Software was utilized to ensure accuracy.

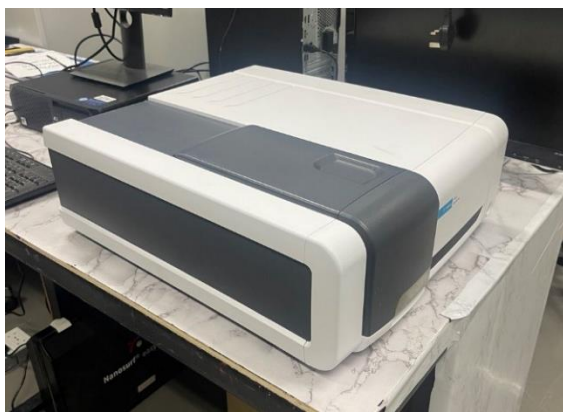


Figure 3.7: Agilent Cary 60 UV-vis machine.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Material characterization

4.1.1 X-ray diffraction (XRD)

XRD is a powerful technique used to analyze the structural attributes of materials. It can be used to find the crystallization and phase structures in metals, polymers and composites [197]. As depicted in Figure 4.1, the XRD profile of the PLA base sample fabricated through FDM revealed two notable peaks at 2θ angles of 16° and 27° . Prior research has reported that PLA in filament form typically displays four distinct diffraction peaks at approximately 15° , 17° , 19° , and 23° , corresponding to the α -crystalline phase [198], [199]. This configuration which impacts its physical and thermal properties, such as rigidity and resistance to heat [200]. Therefore, it appears that the FDM process can alter the crystalline structure of PLA. The characteristic peaks observed in filament form tend to disappear following the extrusion and deposition steps during printing [198]. This structural change is likely due to the rapid heating and cooling experience during the FDM process.

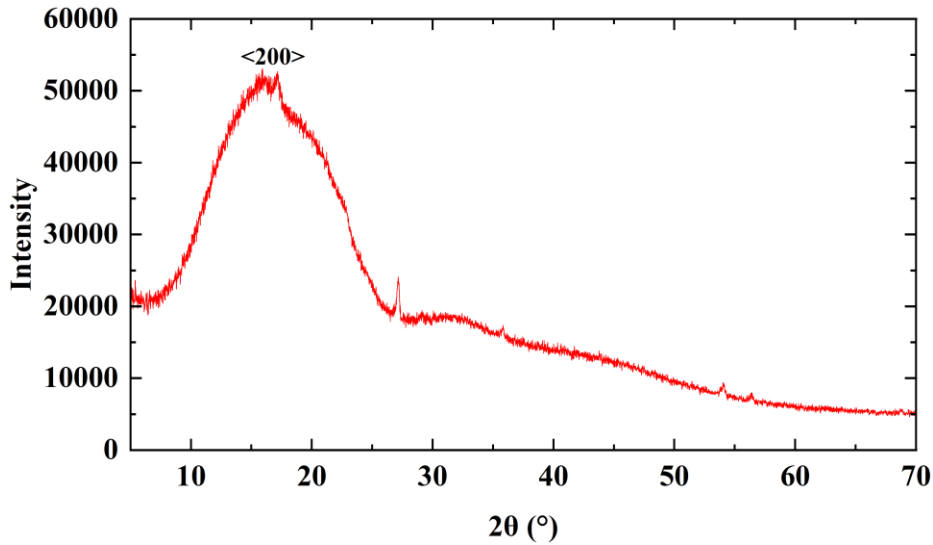


Figure 4.1: XRD results for AM PLA base.

Diffraction patterns of PLA show strong crystalline peak at $\langle 200 \rangle$ (16.15°) that show the presence of low amorphous regions [201]. In a similar work, Ambrus et al. [202] compared the PLA peaks from granules and 3D printed parts and concluded no crystallization in the PLA samples with amorphous structure. However, they observed strong crystalline peaks in the PLA granules. They attributed the change from crystalline to amorphous structure to the increased cooling rate during the 3D printing process and the large temperature difference between the nozzle and the bed. It should be noted that compared to PLA composites, PLA displays peaks at lower angles which indicates a decrease in interlayer spacing and an increase in the amorphous regions in the material [201].

It is well known that the amorphous regions in PLA samples provide increased toughness than crystalline samples [203]. This is useful in SS applications because it provides higher stiffness and structural support. The thermal properties of PLA FDM samples can also be affected by the presence of amorphous regions as they usually offer lower thermal conductivity compared to their crystalline counterparts [204]. Research shows that the use

of materials with high thermal conductivity increases the efficiency of SS devices [205]. However, as the AM PLA samples exhibit a semi-crystalline structure, a moderate thermal conductivity is expected [206]. Compared to crystalline materials such as metals, polymers such as PLA exhibit low thermal conductivity but are more cost-effective.

4.1.2 Fourier transform infrared spectroscopy (FTIR)

The FTIR analysis was also performed on the PLA base to examine its molecular structure and verify the presence of functional groups (Figure 4.2). Characteristic peaks from experimental results confirmed the key functional groups such as carbonyl and ester linkages. The analysis offers insight into the molecular fingerprint of PLA, aiding in its identification and quality assessment [207]. A comprehensive listing of the observed wave numbers (cm^{-1}) and their corresponding molecular vibrations is presented in Table 4.1.

As depicted in (Figure 4.2), the FDM PLA component displays a distinct peak at 1460.87 cm^{-1} , corresponding to $-\text{CH}_3$ stretching vibrations [208], [209]. Additionally, a peak at 1644.09 cm^{-1} , was observed. This peak is associated with the $-\text{C}=\text{O}$ stretching vibrations [198]. Two other peaks at 2853.10 , and 2922.77 cm^{-1} , related to the asymmetric and symmetric stretching vibrations of the $-\text{CH}_3$ (Stretching) groups were also observed [209]. Finally, the broad peak around 3258.76 cm^{-1} can be assigned to the stretching vibration modes of $-\text{OH}$ groups belonging to hydroxyl groups and adsorbed water [210].

Belaid et al. [198] identified the key characteristics of PLA film and attributed the 1740 cm^{-1} peak to $\text{C}=\text{O}$ stretching of carbonyl groups. A similar peak (1644.09 cm^{-1}) was also observed in the FDM PLA samples, while a broad absorption between 2900 cm^{-1} was linked to hydroxyl groups [198].

The infrared spectrum of PLA from FTIR results exhibited distinct absorption bands that are indicative of ester functionalities. Specifically, the peak observed at 1644.09 cm^{-1} correspond to the carbonyl (C=O) and C–O stretching vibrations of the ester groups [209], [210]. These spectral features confirm the successful formation of ester linkages, which result from the condensation reaction between the hydroxyl and carboxyl groups during the polymerization of lactic acid. This gives the material a higher heat absorption, which is an important advantage for the solar still basin. The higher the basin heat absorption, the higher the water temperature, and consequently, the greater the water production.

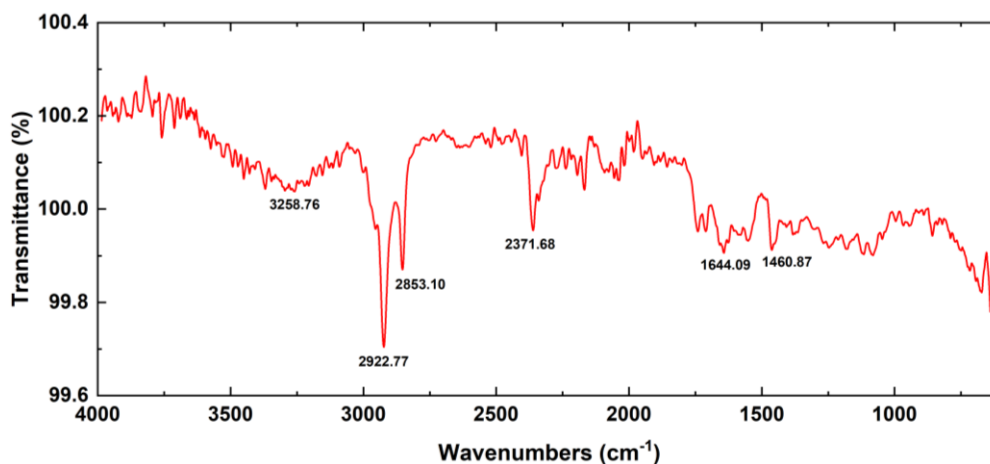


Figure 4.2: FTIR results for AM PLA base.

Table 4.1: PLA compounds.

No.	Functional Group	Standard Frequency (cm^{-1})	PLA (cm^{-1})
1	-OH	2400-3400	3258.76
2	-CH ₃ (S)	2850 – 3000	2922.77
			2853.10
3	-C=O	1640 – 1820	1644.09
4	-CH ₃ (B)	1375 - 1475	1460.87

4.1.3 Thermogravimetric analysis & Differential scanning calorimetry

TGA & DSC was also performed on the AM PLA basin to evaluate the thermal stability [211]. TGA measures the weight changes in a material as it is gradually heated, providing insights into its thermal behavior and composition. TGA also enables the detection of moisture content and volatile compounds present in a sample. When polymers are subjected to elevated temperatures in an oxygen-free environment, such as an inert atmosphere with argon, limited carbonization and coking are likely to take place [212]. However, when polymers are heated under aerobic conditions, they typically undergo full combustion [212]. This results in the breakdown of the polymer chains into simpler volatile compounds like carbon dioxide (CO_2), water (H_2O), and other gaseous byproducts.

Figure 4.3 shows the TGA curves and derivative thermograms (DTG) to study the thermal degradation behavior of pure PLA under an argon atmosphere. The rapid degradation of PLA was observed after the initial degradation point (corresponding to 5% weight loss). Furthermore, the PLA samples recorded a 50 wt% at 359°C. Approximately 95% of the material's mass was lost rapidly after this phase, indicating a sharp decomposition with a 1.33 wt% (1.32 mg) residue, indicating the presence of coking and carbonization (Table 4.2).

Belaid et al. [198] conducted TGA on FDM PLA samples to examine their thermal stability. Their results indicated an initial weight loss of approximately 1% below 200°C, which was attributed to the evaporation of adsorbed moisture. A more substantial weight reduction occurred between 300°C and 400°C, corresponding to the thermal degradation of PLA. Similar to the FDM PLA results (Figure 4.3b), their DTG curve revealed that the peak degradation temperature for PLA was also around 366°C. In contrast, the FDM

PLA/TPU composites studied by Chen et al. [213] presented showed that the composite samples exhibited improved thermal resistance when compared to pure PLA samples with a lower percentage weight loss than pure PLA due to the presence of thermoplastic polyurethane (TPU). However, compared to their results (wt (%) 0.68%) the FDM PLA samples (Figure 4.3a) achieved a lower weight loss (wt (%) 1.33 %) due to the higher temperature range [213].

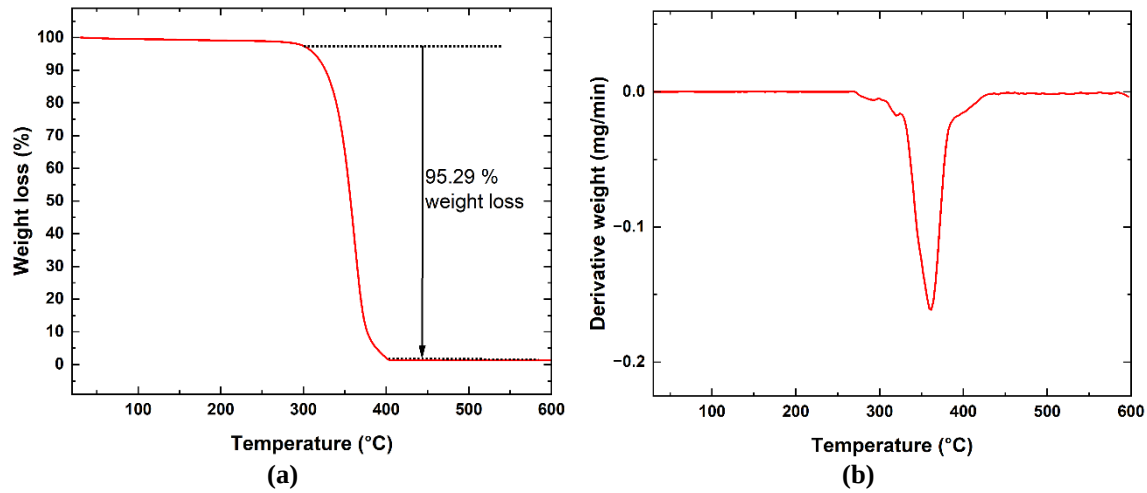


Figure 4.3: (a) TGA (b) DTG results for AM PLA base.

Table 4.2: PLA TGA / DTG results.

	T5 (°C)	T50 (°C)	Residual wt (%)	DTG Peak (°C)
PLA	284±0.32	359±0.43	1.33±0.03	359±0.43

DSC analysis was also conducted to study the thermal transitions of AM PLA basin [214]. The analysis was used to analyze the solid-to-liquid transformations, melting point, and crystallization temperature. Furthermore, the Glass Transition Temperature (T_g) and degree of crystallinity (X_c) were also studied to assess the mechanical performance and internal structure of the AM PLA basin.

The DSC thermogram depicted in Figure 4.4 exhibits three distinct thermal transitions characteristic of semicrystalline PLA. A glass transition temperature (T_g) was recorded at 62.8°C. An exothermic crystallization peak (T_c) at 97.4°C was also recorded that is used to define the change from amorphous to crystalline structure. Finally, an endothermic melting transition at 170.6°C was also observed [215]. Enthalpic calculations revealed a crystallinity degree (X_c) of ~35%, derived from the ratio of melting enthalpy ($\Delta H_m = 33$ J/g) to the theoretical value [219] (Table 4.3).

A study conducted by Belaid et al. [198] explored the crystallinity (X_c) of FDM PLA components. Their analysis revealed a similar crystallinity to the FDM PLA samples observed in this study. However, the addition of GO exhibited an X_c of approximately 45%. This enhancement in crystallinity from 35% to 45% was linked to the introduction of graphene oxide (GO). However, they did not observe any significant change in the T_m and T_g . The crystalline degree ($X_c\%$) plays a critical role in material performance as increasing the crystallinity contributes to enhancing the mechanical stability of the material, enabling it to better withstand external stress without deformation or failure.[216]. Finally, in high-temperature environments, T_g plays an important role in the performance of SS. A reasonable T_g (62.8°C) as observed with the FDM PLA samples is preferred to prevent degradation in the basin properties during SS desalination.

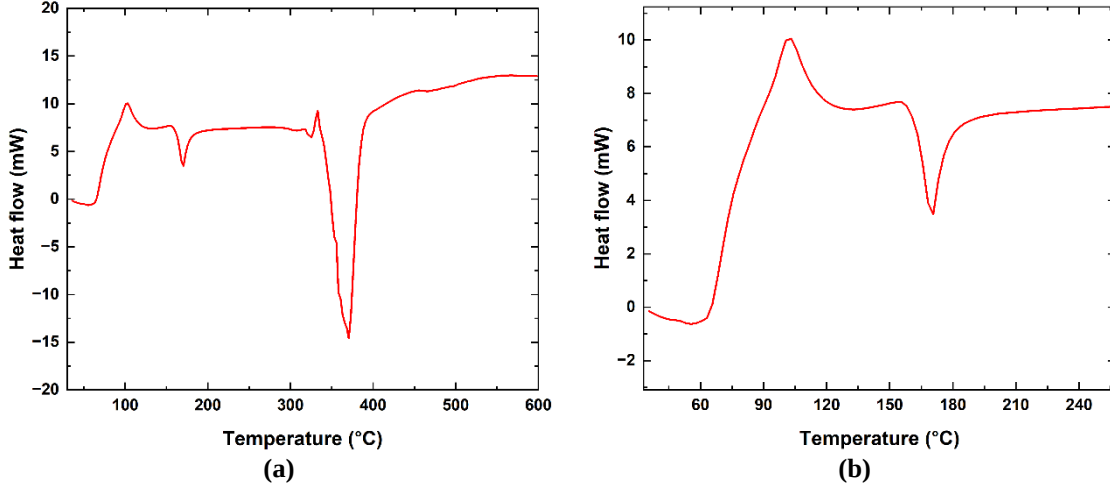


Figure 4.4: (a) Complete DSC results for AM PLA base (b) Subset of the original DSC results for the AM PLA.

Table 4.3: PLA DSC results.

	T _g	T _m	T _c	X _c	ΔH _m
PLA	62.8± 0.78°C	170.6± 0.94°C	97.4± 0.56°C	~35% ± 0.65	33 J/g ± 0.0

4.1.4 Contact angle

Contact angle measurements were performed on the glass and acrylic cover materials employed in the solar still experiments to evaluate their wettability and interfacial properties. As depicted in Figure 4.5, the acrylic cover (Figure 4.5a) exhibited a contact angle of $73.6 \pm 0.89^\circ$ five seconds after droplet deposition, indicative of moderate hydrophilicity ($\theta < 90^\circ$). In contrast, the glass cover (Figure 4.5b) demonstrated a significantly lower contact angle of $55.9 \pm 0.88^\circ$, consistent with high surface energy and strong hydrophilic behavior. According to Young’s equilibrium [217], the lower contact angle of glass correlates with enhanced wettability, promoting the formation of thin, continuous water films that minimize light reflection losses and facilitate rapid droplet runoff. This property is critical in solar still applications, where efficient condensate runoff improves heat transfer and freshwater yield [217].

The droplet run-off behavior was also studied with the covers at a 17° angle to determine the change in the contact angle.

Figure 4.5c shows an increase in the contact angle for both covers at 17° . However, both covers remained hydrophilic as the contact angle of the acrylic cover increased by 3.53%, while that of the glass cover increased by 8.77%.

The results indicate that the acrylic cover has a higher contact angle compared to the glass cover, indicating that it is less hydrophilic. This reduced affinity for water provides a benefit in SS applications, where surface behavior plays a critical role in SS performance. Hydrophobic covers, allow quicker movement of condensed water droplets. This fast movement of the droplets allows continuous formation of new droplets and thereby enhance the performance of the SS [218]. On the other hand, the glass cover, with its more hydrophilic behavior inhibits the creation of fresh droplets and hampers the distillation performance [218]. It has been confirmed that hydrophobic covers encourage water droplet separation, while hydrophilic covers support adhesion [218]. This leads to a notable decrease in performance when using hydrophilic covers, as the rate of condensation and droplet removal becomes less efficient.

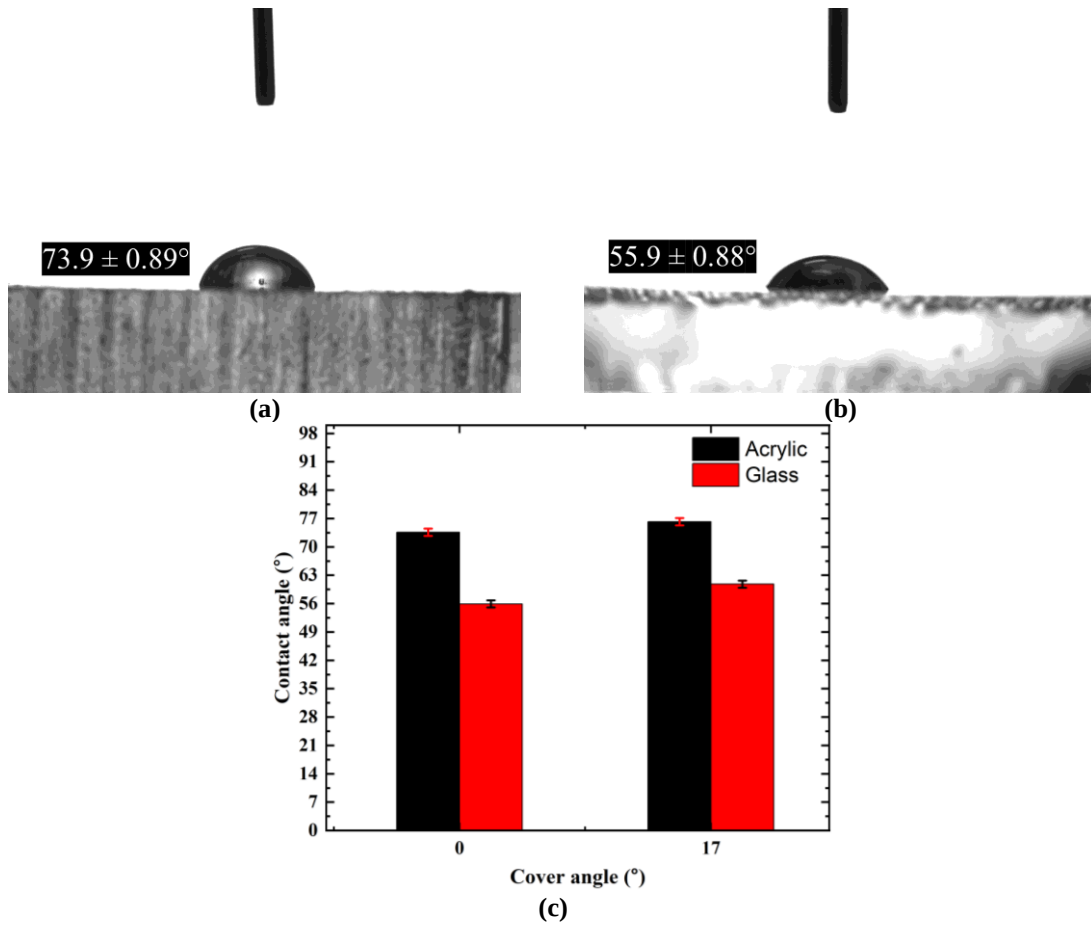


Figure 4.5: Contact angles for (a) Acrylic and (b) Glass covers (c) Acrylic and glass cover contact angles at different cover angle.

4.1.5 Ultraviolet visible spectroscopy (UV-Vis)

Figure 4.6 presents the optical performance of glass and acrylic covers through comparative UV-vis spectroscopy analyses of absorption, reflectance, and transmittance. As illustrated in Figure 4.6a, the absorption spectra reveal distinct wavelength-dependent behaviors. Glass exhibited reduced absorption beyond 310 nm, whereas acrylic maintained measurable absorption up to 385 nm. This suggests that acrylic can absorb a higher percentage of the shorter-wavelengths which might result in a higher surface temperature. It is well known that the covers in SS applications should absorb as little solar radiation as

possible, because this increases the cover temperature. The temperature difference between the water in the basin and the cover is an important factor that affects the SS performance. Therefore, it is important that the cover used has low absorption that results in a high temperature difference and yield.

Transmittance data (Figure 4.6b) highlights the superior performance of acrylic cover, with a higher transmittance % across the visible spectrum compared (380 – 700 nm) to glass. However, glass shows high transmittance in the lower wavelengths. Transmittance data revealed that acrylic exhibits a transmittance of approximately 92% in the visible spectrum, marginally higher than glass (90%) due to reduced reflection losses. This enhanced transmittance should enable acrylic to transmit more incident solar energy to the water interface, thereby improving the basin water temperature and evaporation rate [219].

Ameri et al. [220] conducted a study on the transmittance of glass and acrylic covers and concluded that at short wavelengths, the glass cover outperforms the acrylic cover in transmittance. However, at larger wavelengths, the acrylic cover begins to outperform the glass cover. Murtadha [219] studied the acrylic covers with different thicknesses and reported a higher transmittance of acrylic cover than glass. In addition, their acrylic covers exhibited a transmittance of over 90% which decreased with an increase in the angle of the solar still.

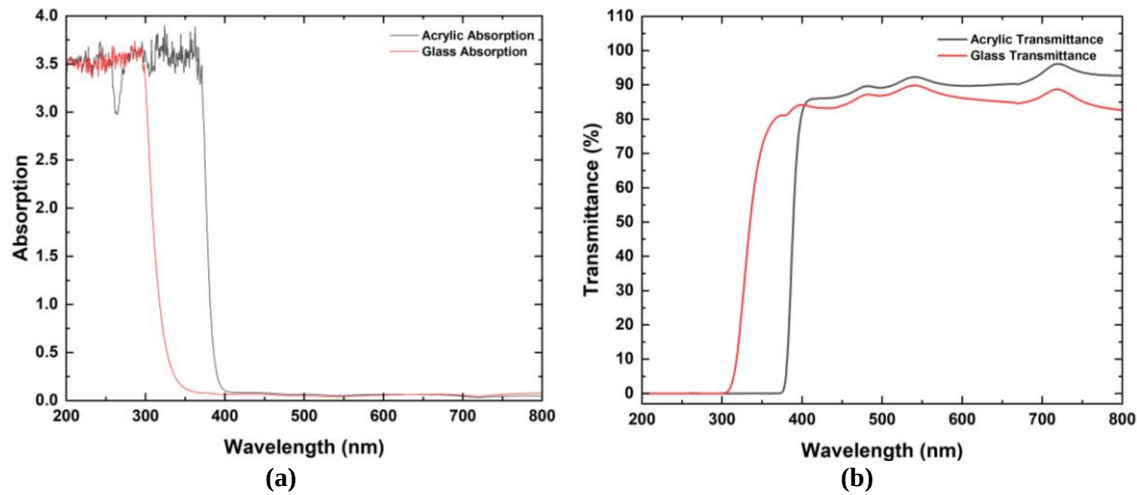


Figure 4.6: UV-vis results for acrylic and glass covers. (a) Absorption (b) Transmittance.

4.2 Solar still

The solar desalination process utilizes the absorbed solar by the saline water to induce a phase change at the liquid-air interface. Water molecules at the surface attain sufficient kinetic energy to overcome intermolecular cohesive forces, transitioning into the vapor phase through evaporative mass transfer. This vapor, laden with latent heat of vaporization, ascends via natural convection to the cooler inner surface of the inclined cover. A thermal gradient between the humid air-vapor mixture and the cover surface facilitates condensation, forming microdroplets through nucleation that are collected as distillate. The SS experiments are presented in this section Experiments with glass and acrylic covers were conducted to determine the optimal cover. Then, a comparison between different water levels was performed to assess the effect of water level on fresh water production. Finally, a comparison was conducted between different basin geometries (such as flat, V-shaped, and sinusoidal) and their effects.

4.2.1 Effect of covers

A comparative experiment was conducted to evaluate the influence of cover material (glass versus acrylic) on the SS performance. Both SS were tested under identical ambient conditions to ensure a fair assessment. The ambient parameters during the trial are illustrated in Figure 4.7.

Figure 4.7a displays solar radiation levels throughout the day. The experiments started at 7 AM with 68 W/m^2 of solar radiation that began to rise at a rate of 157.6 W/m^2 per hour until it reached its maximum at 12 PM with 856 W/m^2 . Then, the solar radiation started to decrease at a rate of 155.5 W/m^2 per hour until it reached 234 W/m^2 at 4 PM. Since the efficiency of solar still is directly linked to the amount of absorbed solar energy, higher radiation levels typically result in increased evaporation rates and improved productivity [103].

Figure 4.7b presents the wind speed throughout the day. The results show minor variations in the wind speed throughout the day (between $1 \pm 0.55 - 2.7 \pm 0.55 \text{ m/s}$). The highest wind speed was recorded at 4 PM (2.7 m/s), while at 7:00 AM and 1:00 PM, it reached its lowest speed of 1 m/s . It is worth noting that the maximum change in wind speed (1.4 m/s) occurred between 7:00 AM and 9:00 AM. The effect of wind velocity has been confirmed by numerous publications [118] (Figure 2.28). Therefore, it is important to study the wind speeds as elevated wind speeds can adversely affect SS efficiency by enhancing convective heat losses, which reduce the internal temperature of the system and block the evaporation process [121]. On the other hand, it is well-known that the SS yield improves with a reduction in glass cover temperature [119]. Drop in cover temperature due to high wind

speed can cause an increase in the temperature difference which leads to an increase in water production [111].

Lastly, Figure 4.7c illustrates the ambient temperature measurements. Results show an initial drop in the ambient temperature by 0.1°C between 7:00 AM to 8:00 AM. This may be due to the rise in wind speed during that time. The temperature rose from 13.5°C to 20.3°C from 8:00 AM to 12:00 PM, with a change of 1.7°C/hr . A strong correlation was observed between the ambient temperature and solar radiation as the maximum ambient temperature was also observed around noon (Figure 4.7a). The ambient temperature remained stable from 12:00 PM to 1:00 PM at 20.3°C . The temperature reached 18.5°C at 4:00 PM, with a rate of 0.6°C/hr . The lowest ambient temperature was recorded at 8:00 AM. (13.5°C), while the highest was recorded at 12:00 PM and 1:00 PM (20.3°C). This rise in ambient temperature, driven by higher solar input, is expected to enhance the water evaporation and, consequently, freshwater yield [112].

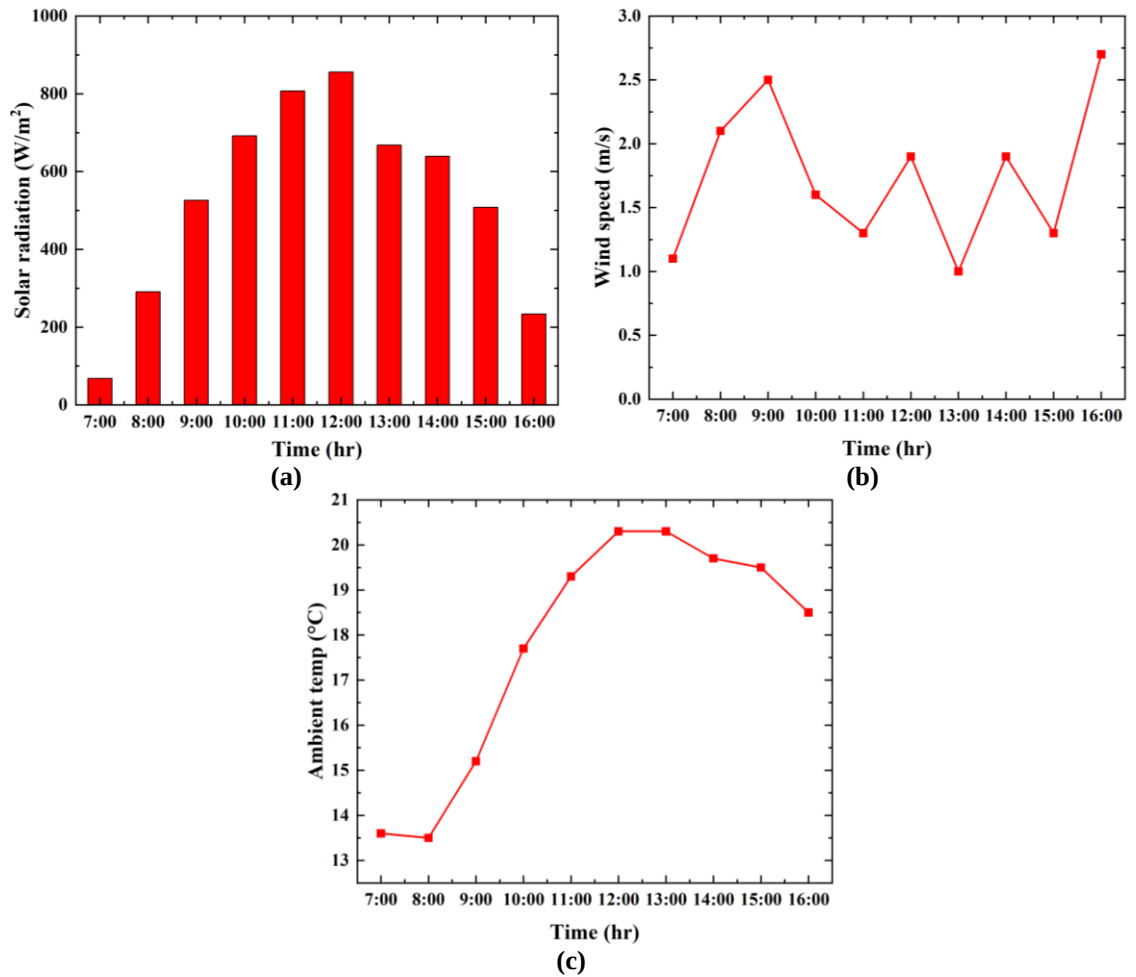


Figure 4.7: Ambient parameters for studying the effect of covers (a) Solar radiation (b) Wind speed (c) ambient temperature.

The performance of SS with glass and acrylic covers was further analyzed by comparing water and cover temperatures. Figure 4.8a illustrates the variations in these temperatures throughout the day. From the start of the experiment at 7:00 AM., the water with the glass cover was 1.2 $^{\circ}\text{C}$ higher than the water with the acrylic cover. The water temperature for both the glass and acrylic covers began to increase at a rate of approximately 5 $^{\circ}\text{C/hr}$. At 8:00 AM, the temperatures were 14.5 $^{\circ}\text{C}$ and 13.3 $^{\circ}\text{C}$, respectively, and continued to rise until reaching their highest values at 1:00 PM. A temperature of 40.4 $^{\circ}\text{C}$ was recorded for

the water temperature in the glass SS and a slightly lower temperature of 37.2°C was recorded for the acrylic SS at 12:00 PM. This was followed by a 4.2°C/hr decrease in water temperature for the glass SS, reaching a temperature of 27.7°C at 4:00 PM. The water temperature in the acrylic SS decreased at a rate of 2.5°C/hr, reaching a temperature of 26.9°C at 4:00 PM. The largest percentage difference (13%) between the water temperatures of the glass and acrylic covers was at 1:00 PM. It was observed that the water temperature was consistently higher for the glass cover than the acrylic cover. This is due to the transmission spectrum of the various covers. Results from the UV-Vis (Figure 4.6b) show that acrylic covers transmit in a wider range of wavelengths than glass cover. This allows more solar energy to reach and heat the cover resulting in higher temperatures.

Figure 4.8b shows cover temperatures for glass and acrylic SS. The glass cover exhibited a 2.2°C higher temperature than the acrylic cover at 7 AM. The cover temperatures for both the glass and acrylic SSs rose and followed a similar trend to that observed in the water temperature. The glass cover reached its highest temperature at 1 PM (32.7°C), while the acrylic cover reached its peak temperature at 12 PM (28.2°C). This trend can be explained by the absorption spectrum (Figure 4.6a) of acrylic and glass covers. As acrylic cover showed higher absorption wavelength spectrum than glass, it reached the maximum temperature notably faster than glass. It should be noted that between 9 AM and 10 AM, the glass cover temperature changed by only 0.3°C. This slight increase may be attributed to the wind speed (Figure 4.7b) and its possible effect on SS covers [111]. Subsequently, both cover temperatures began to decrease at a rate of 3.2°C/hr for the glass cover and 2.1°C/hr for the acrylic cover until they reached 23°C and 19.8°C, respectively, at 4 PM. It is also noteworthy that the highest temperature difference (25%) between the glass and

acrylic covers occurred at 1 PM. However, in the context of SSs, a lower cover temperature is more desirable [221]. This is because cooler cover surfaces enhance condensation efficiency. When hot vapor rises and comes into contact with a cooler surface, it condenses more rapidly into water droplets. Therefore, the reduced temperature of the acrylic cover creates a more suitable environment for efficient condensation.

It is crucial to examine the temperature difference between the water and the cover to assess the overall performance of the SS. A 1°C temperature difference (Figure 4.8c) was recorded between the acrylic and glass cover at the beginning of the experiment at 7:00 AM. This was followed by a slight temperature reduction (0.6°C) with the acrylic cover showing a higher temperature difference than glass. The maximum temperature difference for the acrylic cover (9.7°C) was recorded at 1:00 PM and at 12:00 PM for the glass cover (7.9°C). It is worth noting that at 10:00 AM, the glass cover had a higher temperature difference than the acrylic cover by 1.5°C . This increase in the glass cover's temperature difference is due to the stability of the glass cover's temperature (Figure 4.8b) between 9:00 and 10:00 AM. The maximum temperature difference was followed by a reduction in temperature difference for both covers. At 4:00 PM, the temperature difference of the acrylic cover reached 7.1°C , with a rate of change of 0.86°C/hr , while the glass cover's temperature difference reached 4.7°C , with a rate of change of 0.8°C/hr . Numerous studies have confirmed that a higher temperature difference between the water and the cover promotes increased condensation and thus improves freshwater yield [156], [157], [158]. This thermal gradient suggests that solar still equipped with acrylic covers offer higher condensation potential, making the acrylic material a more effective choice for enhancing water productivity in SS applications.

Several researchers have conducted studies on glass and acrylic cover materials using different devices. Ameri et al. [220] conducted a study on solar air heaters (SAHs) with various cover materials, including glass and acrylic. They found that the glass cover had a higher cover temperature than the acrylic cover. Sambare et al. [222] also conducted a study on tubular solar stills (TSS) using four different cover materials and found that the water temperature and productivity under the glass cover was higher than that from the acrylic cover. (Figure 4.6c) The higher water temperatures observed with FDM glass SS could be due to differences in the type of glass. In addition, in the current study, the acrylic SS recorded the highest transmittance (Figure 4.6c). Finally, Shatar et al. [223] conducted a study on a single slope SS using thermoelectric cooling. They reported that the water and cover temperature of the glass SS was higher than that of the conventional SS. Their higher production could be due to the higher condensation rates achieved due to the presence of active cooling device.

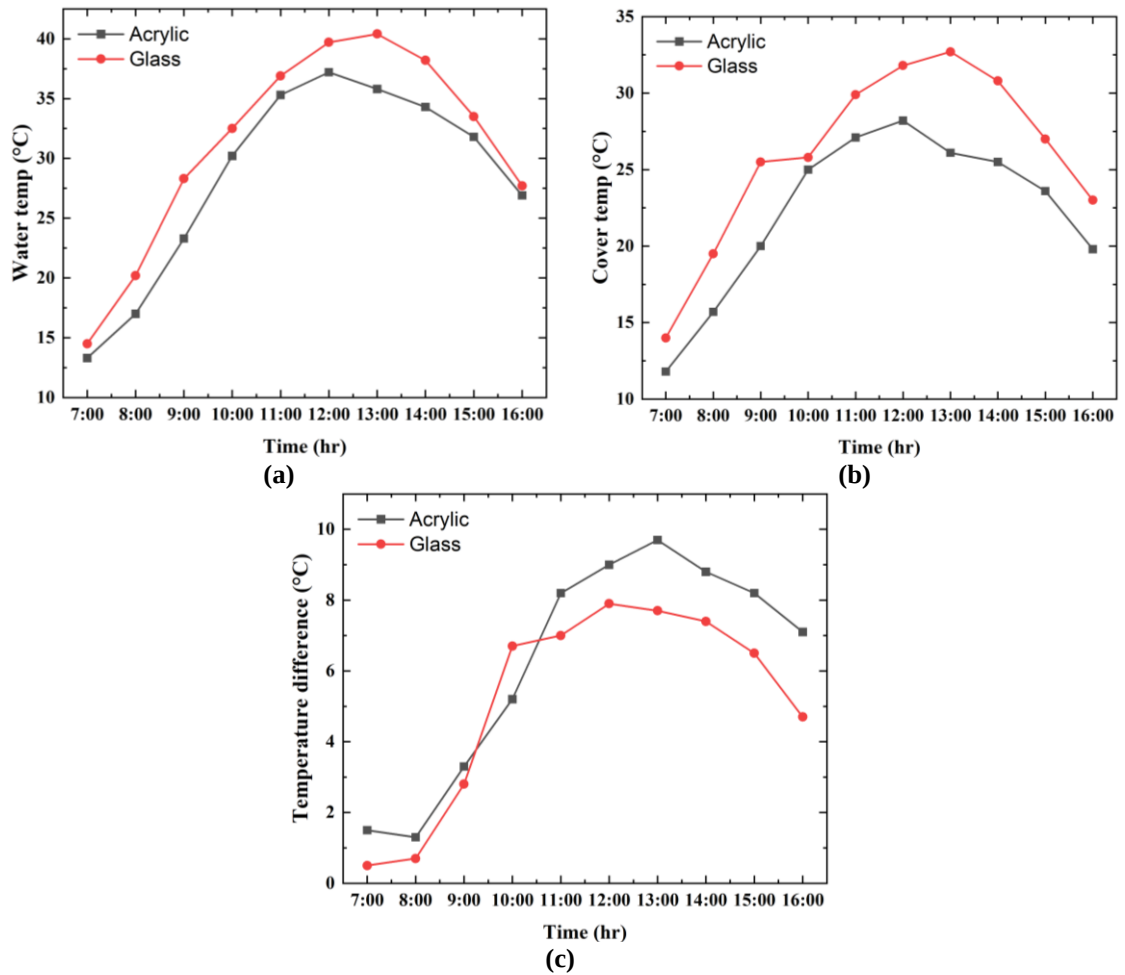


Figure 4.8: SS performance with glass and acrylic covers. (a) Water temp (b) Cover temp (c) Temperature difference.

Figure 4.9 presents a comparative evaluation of the distilled water output from two SSs. The production trends reveal that the acrylic SS shows higher yield from around 10:00 AM, with a sustained increase in output up to 1 PM. Conversely, glass SS shows a lower rate of water collection with a sustained reduction in yield after 2:00 PM. The increase in the average water production rate from 8:00 AM to 12:00 PM for both the glass and acrylic cover SSs were calculated as 28 mL/hr. On the other hand, the average reduction in water production rate after 1:00 PM for the glass and acrylic cover SSs was calculated as 26.7

mL/hr and 21.9 mL/hr, respectively. This indicates that the acrylic cover maintained production after a reduction in solar radiation due to its high absorptivity. Quantitatively, the acrylic SS achieved a total water output of approximately 660.7 mL, whereas the glass SS produced about 600.5 mL.

These findings indicate that the acrylic cover contributes more effectively to the overall efficiency of the SS. The higher temperature difference between water and the acrylic cover, which enhances condensation, combined with the stable yield pattern throughout peak sunlight hours, supports the selection of acrylic as the preferred cover material for maximizing distillate output.

Sambare et al. [222] conducted a study using the TSS system with glass and acrylic covers, and concluded that the total water yield of the glass cover was higher than that of the acrylic cover. This difference may be attributed to a different type of glass cover with higher transmittance. Moreover, Shatar et al. [223] also conducted a study on the water production of a single-slope SS using thermoelectric cooling with glass and acrylic covers. They reported a close relationship between the temperature difference (water temperature and cover temperature) and the water production: the greater the temperature difference, the greater the water production. They also found that the glass SS had higher water production than the acrylic SS. This superiority may be due to the use of external cooling used in their study.

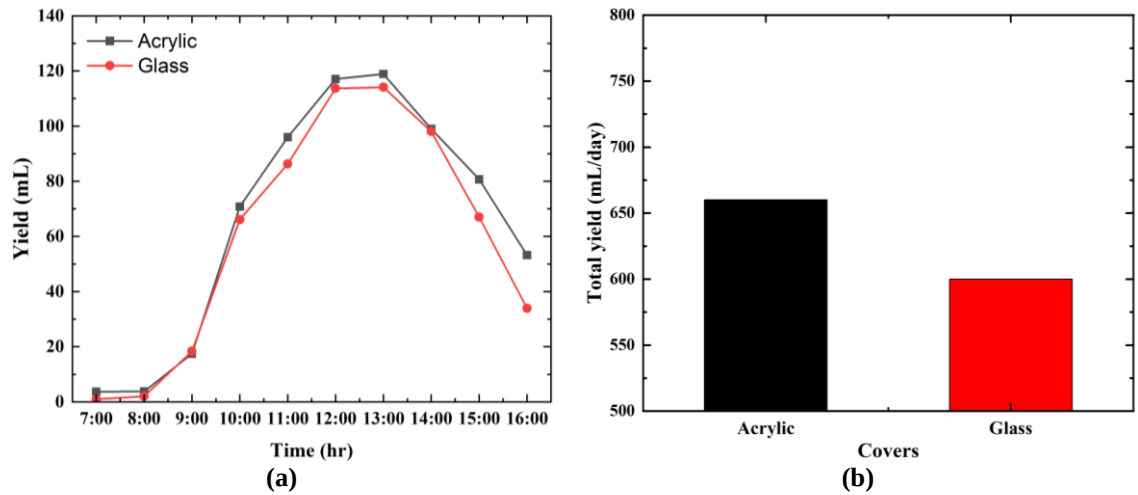


Figure 4.9: The hourly distillate yields for acrylic and glass covers (b) Total yield.

Mechanically, acrylic demonstrates significantly higher impact resistance compared to glass [224]. This reduces the risk of catastrophic failure during operation despite acrylic's lower density [224], [225]. In this work, a thick acrylic sheet (6 mm) was used to compensate for its lower modulus of elasticity as thin sheets exhibit deflection under high temperature. This deflection/warping might cause vapor leakage during the SS experiments. This leads to the conclusion that design choices can be used to mitigate defects (such as leakage due to warping) due to deformation under concentrated solar irradiance. Conversely, acrylic's lower surface hardness increases susceptibility to abrasion, necessitating careful handling during maintenance [225]. Material selection thus represents a compromise between optical efficiency, structural durability, and thermal resilience [226], [227].

4.2.2 Effect of depth of water and basin surface

The effect of water level and basin geometry was investigated with the acrylic cover as the best choice for SS applications. This study, with different water levels (100 mL, 150 mL, and 200 mL), was structured across three days with consistent ambient parameters to

ensure consistency in comparison of SS performance. Each base geometry (flat, V-shaped, and sinusoidal) was also studied with the varying water levels.

Results from the environmental parameters show similar results for solar radiation, wind speed and ambient temperatures (Figure 4.10). Noticed, after 9:00 AM, the solar radiation on the 200 mL day was higher than during the other experiments, followed by the 150 mL day, and lastly the 100 mL day. The highest percentage difference was observed at 12:00 PM between the solar radiation on the 200 mL day and the other days, with a value of approximately 9%. However, a similar level of solar radiation was observed for the three days (Figure 4.10a). However, a higher solar radiation was observed between the current and the previous (effect of cover) experiments (Figure 4.8c). Wind speed (Figure 4.10b) also showed consistent results with slight variation between 1 m/s and 3.5 m/s. The highest wind speed recorded over the three days was 200 mL, then 150 mL and finally 100 mL. Finally, ambient temperature plots across the three days displayed a high similarity, especially during peak sunlight hours. It should be noted that a slightly higher ambient temperature was recorded for the experiment conducted with 200 mL. However, the temperature differences were minimal and therefore, any differences observed in the SS performance can be confidently attributed to the tested variables of water level and base shape rather than external ambient parameters.

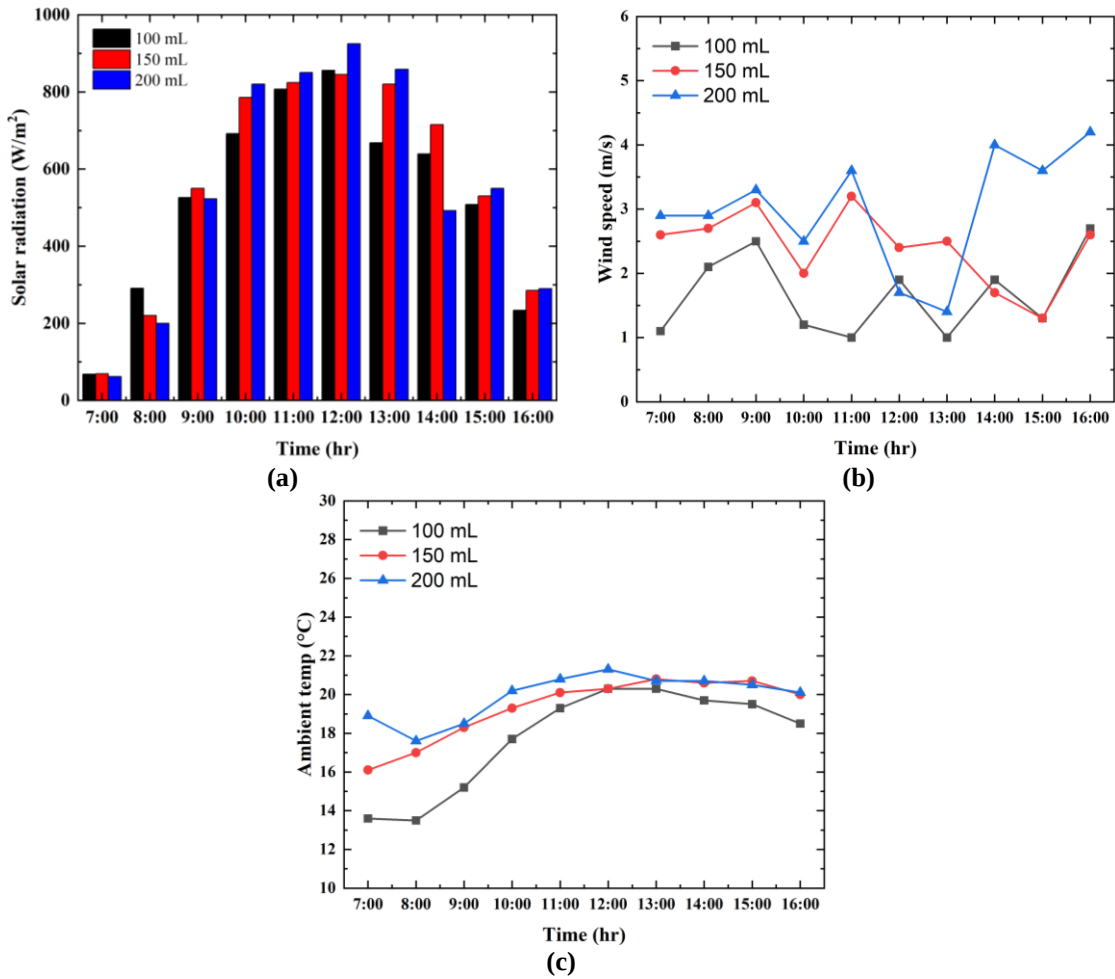


Figure 4.10: Ambient parameters for three days of experiments. (a) Solar radiation (b) Wind speed (c) ambient temperature.

(a) Effect of water depth

The impact of varying water volumes (100 mL, 150 mL, and 200 mL) under similar ambient conditions is shown in Figure 4.11a. The 200 mL water level produced the highest temperature, followed by the 150 mL and 100 mL during the initial phases. This trend correlated with the slightly higher ambient temperatures recorded on that day Figure 4.10c. However, as solar radiation intensified, the lower water level SS (100 mL) outperformed the larger volumes Figure 4.11a. This outcome supports the concept that lower water volumes heat up rapidly, despite being exposed to marginally cooler ambient conditions

[124]. The temperature rise in the 100 mL sample enhanced the evaporation rate, thereby improving the overall efficiency of the SS. Interestingly, the 200 mL volume exhibited higher temperatures than the 150 mL, a result that can be attributed to the higher ambient temperature. The highest water temperature for all experiments was observed at 12 PM, for 100 mL, then 200 mL, and finally 150 mL solar stills. Figure 4.11b shows that cover temperatures across the different water levels naturally follows the trend of the water temperature due to identical conditions. Therefore, an increase in the water temperature, increases evaporation. The increased evaporation rate results in an increase in cover temperature. Analysis of temperature difference (Figure 4.11c) shows that the 100 mL water level has a significantly higher temperature difference between the cover and the water compared to the 150 mL water level (by about 2°C) while the 200 mL water level shows an even lower temperature difference.

Figure 4.11d presents a clear comparison of freshwater yield across varying water levels, revealing that the 100 mL SS produced more distillate than higher SS volumes. At 12 PM, the water production for the 100 mL exceeded significantly by about 70 mL. However, the water production for the 200 mL solar still surpassed that of the 150 mL sample at 1 PM. This may be due to a drop in the cover temperature for the 200 mL and a rise in the cover temperature for the 150 mL. Specifically, the 100 mL SS achieved a total output of ~744 mL, outperforming the 150 mL and 200 mL trials, which yielded 563 mL and 537 mL, respectively (Figure 4.11e). This outcome confirms that smaller volumes can lead to greater distillate production [125]. Therefore, an increase in the initial water volume requires more time and energy to elevate the water temperature that reduces production

due to lower evaporation rates. Similar observations have also been recorded by several works [125], [128].

In summary, the findings demonstrate that smaller water volumes offer an advantage in SS processes. Due to their lower mass, they reach high temperatures quickly, thus initiating evaporation and freshwater production sooner than larger volumes. This behavior underlines the importance of carefully selecting water quantities to enhance the efficiency of SS systems. Compared to the 150 mL and 200 mL, the productivity of the 100 mL SS (Figure 4.11d) between 8:00 AM and 12:00 PM shows a significant increase. This may be due to the higher water temperatures (Figure 4.11a). The rate of change of water temperature between 7:00 AM and 12:00 PM was recorded as 5.44°C/hr. In contrast, the rate of change for 150 mL and 200 mL SS was recorded around 3.8°C/hr. Therefore, the smaller water quantity records a higher rate of change in temperature and evaporation. Additionally, after 12:00 PM, the productivity of the 100 mL SS gradually decreases as small water volumes store lower heat. This lower heat cannot sustain evaporation during periods of lower solar radiation resulting in lower production during low solar intensity. It is observed that the temperature drop rate in the 150 mL and 200 mL SS is lower than that of the 100 mL SS. This explains the presence of large productivity gap for the 100 mL SS during high solar radiation (7:00 AM and 12:00 PM).

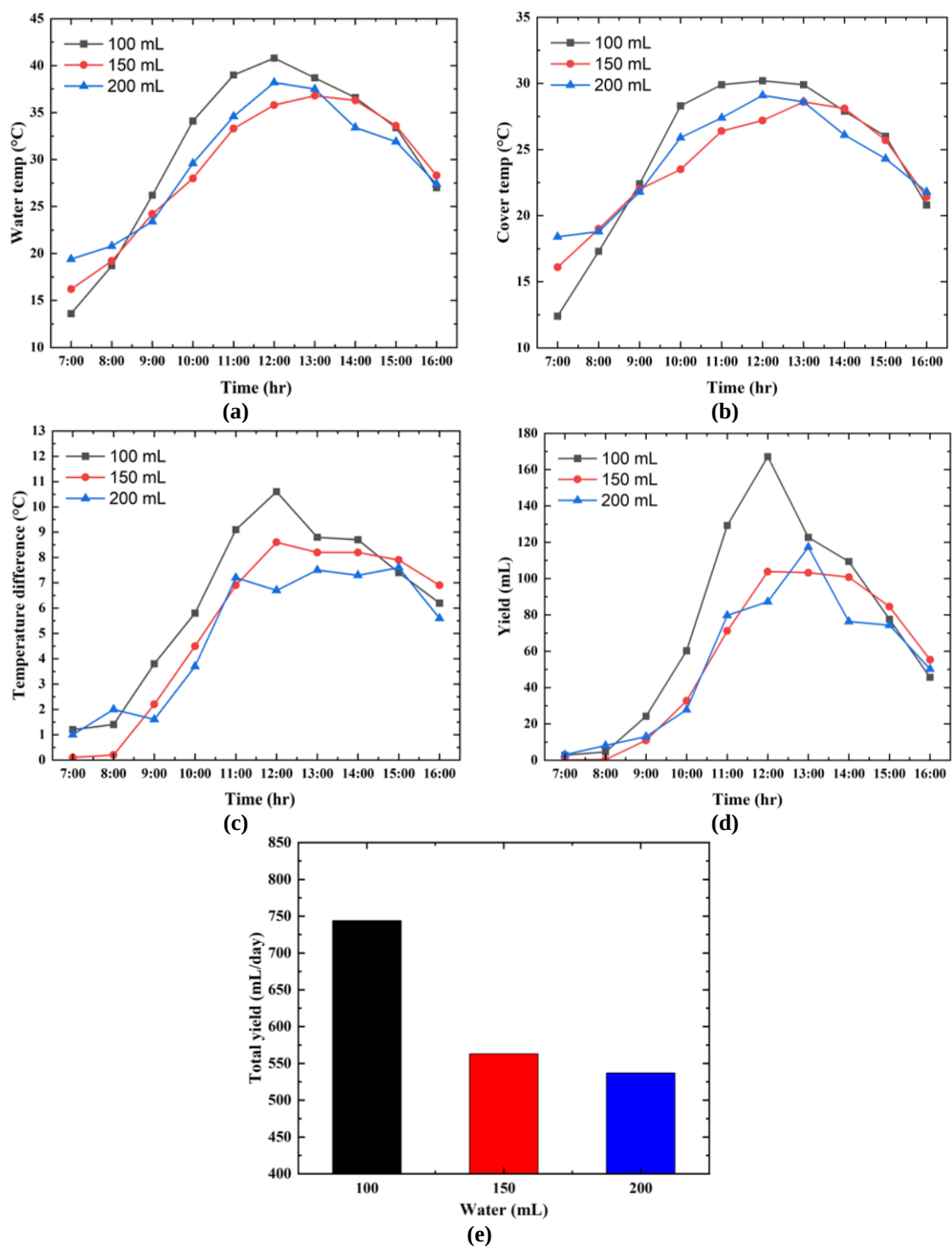


Figure 4.11: (a) Water temperature, (b) Cover temp, (c) Temperature difference, (d) Yield with varying water volumes, and (e) Total yield.

(b) Effect of basin geometry

The optimized cover (acrylic) and water level (100 mL) were used to evaluate the effect of basin geometry (flat, V-shaped, and sinusoidal) on SS performance. The results (Figure 4.12a) revealed a clear advantage for the sinusoidal base in terms of water temperature, followed by the V-shaped, and flat base. This could be explained by the sinusoidal shape of the basin. As the spaces between the peaks fill with water, an overall reduction in water depth is observed. Therefore, a higher yield is expected with sinusoidal base as reduction in water levels leads to an increase in the water temperature and yield. Compared to the flat base, the V-shaped base also showed improved performance over the flat base but fell short of the sinusoidal design. It was observed that the water temperature for the sinusoidal shape was highest after 7:00 AM, and the rate of change was approximately the same for all basin shapes, at 5°C/hr. In a comparative investigation, Gawande et al. [228] analyzed the impact of different basin geometries on the performance of SS. The study evaluated three configurations (flat, convex, and concave) to determine the base shape affects. Their findings demonstrated that the convex basin achieved a higher output, yielding 56.6% more distilled water than the flat basin. Similarly, the concave basin exhibited a 29.2% increase in water production compared to the flat design. The researchers attributed this enhancement to the varying level of water associated with each shape. Both the concave and convex basins held water at depths less than the flat basin, allowing for quicker heating and more rapid evaporation.

Figure 4.12b shows the cover temperature for the different basin geometries. The sinusoidal shape exhibits the highest cover temperature. This aligns with the observed higher water temperature, as increased evaporation leads to more vapor condensation at the

cover, raising its temperature. It should be noted that the rate of change in water temperature and the rate of change in the cover temperature was approximately the same for all geometries (5.3°C/hr). Figure 4.12c shows the difference between water and cover temperatures. It was noted that at 12 PM, the difference between the sinusoidal shape and other shapes was significant, with a difference of up to 1.4°C . However, at 1 PM, the V-shape recorded the highest temperature. The flat base showed the lowest temperature differential, reflecting its relatively less vapor condensation, while the sinusoidal showed the highest temperature differential. Finally, Figure 4.12d highlights the yield from the different basin geometries. During peak solar radiation, the sinusoidal solar still resulted in a yield of more than 30 mL and 50 mL in comparison to the V-shape and flat shape, respectively. The sinusoidal SS exhibited a significantly higher yield at 12 PM than the V shape and the flat shape. This may be due to the higher sun-facing area. On the other hand, the V shape SS exhibits a smaller sun-facing area and a few peaks from the V shape SS might experience partial shading. In general, the area between the peaks might offer a significant evaporation advantage for the sinusoidal and V shape SS if the water level in the SS falls below the surface peaks. Figure 4.12e shows the overall production where the sinusoidal base outperformed the V-shape and flat bases in freshwater production with 744 mL, followed by the V-shape 677 mL, and, the flat base 591 mL, respectively. This reinforces the critical role of geometrical optimization in enhancing SS performance and maximizing water output.

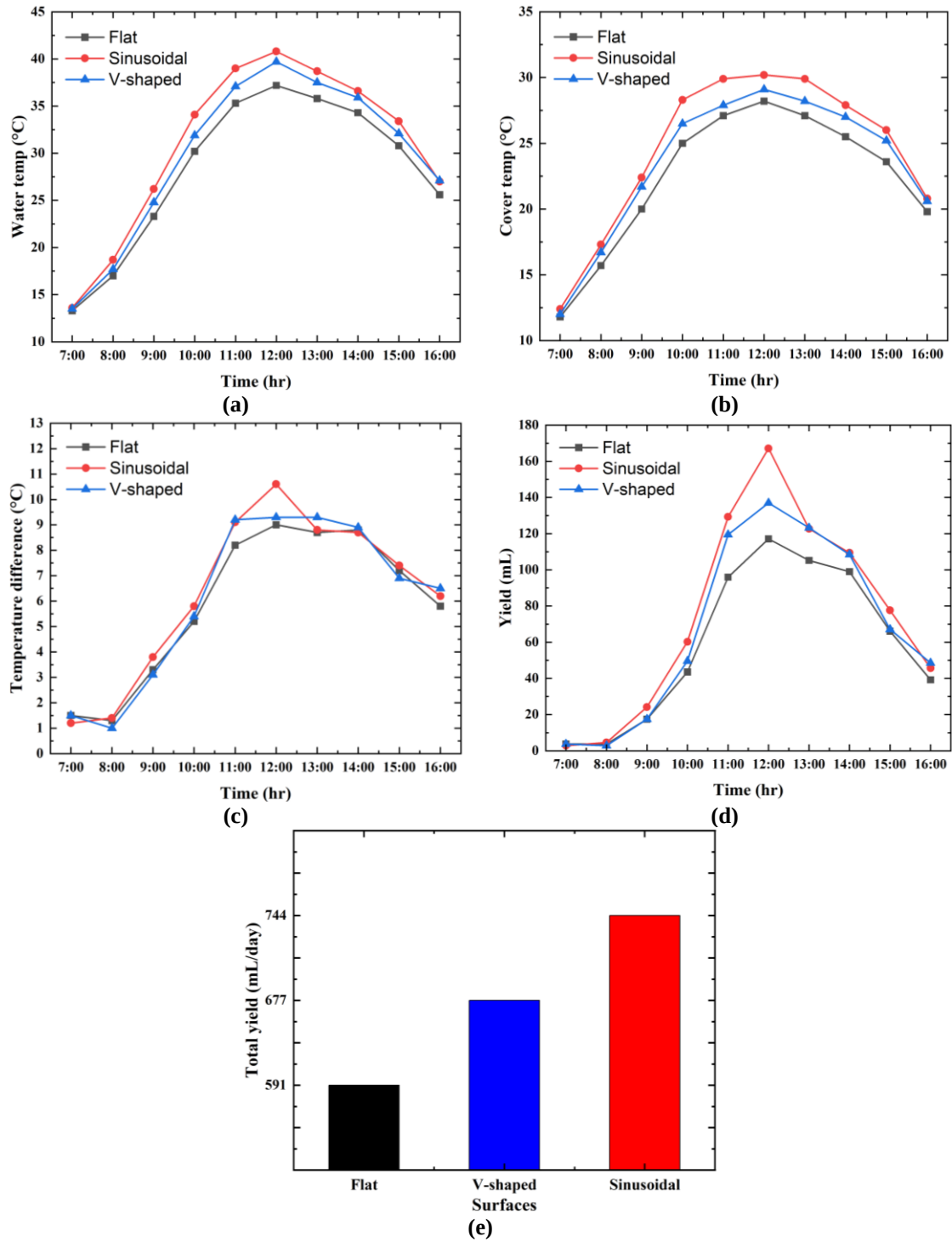


Figure 4.12: Effect geometry of the base on SS performance. (a) Water temp, (b) Cover temp, (c) Temperature difference, (d) Yield, and (e) Total yield.

4.3 Discussion

The contact angle results revealed that the glass cover finds greater hydrophilicity compared to the acrylic cover. This behavior is less desirable in SS applications, as it leads to droplet adhesion, thereby obstructing further condensation. In contrast, the acrylic cover exhibits a higher contact angle that enables continuous droplet formation. The effect of water level with acrylic cover revealed that reducing the water level led to a rise in the SS performance. A lower volume of water will experience higher evaporation rates than large SS basin for the same solar radiation resulting in higher yield. Geometry assessment (sinusoidal, V-shaped, and flat bases) revealed that the sinusoidal base exhibited the highest performance, followed by the V-shaped and flat design. The superior results of the sinusoidal and V-shaped designs can be attributed to their ability to reduce the active water level and increase surface area (Figure 4.13).

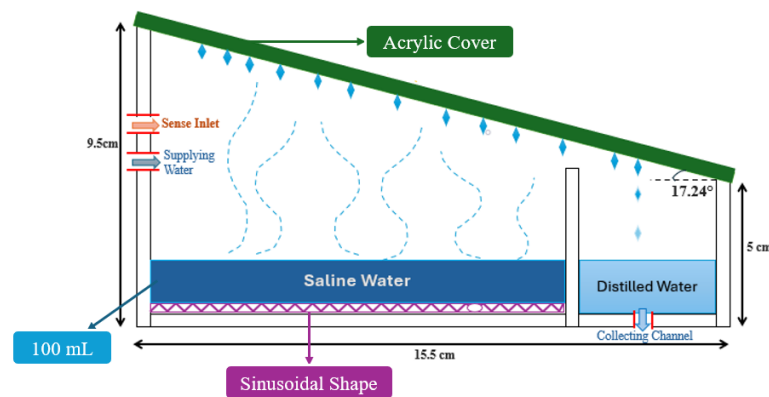


Figure 4.13: Optimal SS with sinusoidal base and acrylic cover.

CHAPTER 5

CONCLUSIONS

The proposed study highlights the potential of integrating AM technology in the development of efficient SS desalination devices. The current work proposes the use of FDM to fabricate and assess the performance of single slope SS with varying basin geometries, water levels and covers. The findings from this research demonstrate the applicability of AM technologies for producing high-quality SS. The main conclusions from this work are given below:

- XRD analysis for the AM PLA base showed distinct semi-crystalline peaks at 16° and 27°. FTIR analysis revealed five distinct peaks that indicated absorption bands characteristic of the ester functionalities in PLA. The TGA and DTG graphs showed that the PLA sample begins initial decomposition at 5% weight loss, followed by rapid decomposition at 302°C. DSC analysis showed the glass transition temperature of 62.8°C while the melting point was calculated as 170.6°C.
- Analysis of glass and acrylic covers showed a larger contact angle (73.9°) for glass. Therefore, compared to glass, the non-hydrophilic nature of acrylic cover promotes the formation and transportation of droplets, resulting in higher yield. UV-Vis analysis exhibits a lower absorption and transmittance for glass cover than acrylic.
- Analysis of different covers showed higher water and cover temperature for the glass cover than acrylic. However, the glass cover showed a lower temperature difference. This resulted in a higher freshwater yield (660.7 mL) than the glass cover (600.5 mL).

- Analysis of water levels highlighted the significance of lower basin levels for highest efficiency. The 100 mL water level resulted in the highest cover and water temperature. In addition, the highest temperature difference and yield was also observed for the 100 mL followed by the 150 mL and 200 mL.
- Different basin geometries were also analyzed in this work. The sinusoidal shape outperformed the other shapes (744 mL), followed by the V-shape (677 mL) and the flat shape (591 mL).
- The results from this research suggest the use of an acrylic cover, a lower water level, and a sinusoidal basin base to enhance the efficiency of single slope SS devices.

REFERENCES

- [1] M. Seifi *et al.*, “Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification,” *JOM*, vol. 69, no. 3, pp. 439–455, Mar. 2017, doi: 10.1007/s11837-017-2265-2.
- [2] M. Seifi, A. Salem, J. Beuth, O. Harrysson, and J. J. Lewandowski, “Overview of Materials Qualification Needs for Metal Additive Manufacturing,” *JOM*, vol. 68, no. 3, pp. 747–764, Mar. 2016, doi: 10.1007/s11837-015-1810-0.
- [3] D. Mahmoud, M. Magolon, J. Boer, M. A. Elbestawi, and M. G. Mohammadi, “Applications of Machine Learning in Process Monitoring and Controls of L-PBF Additive Manufacturing: A Review,” *Applied Sciences*, vol. 11, no. 24, p. 11910, Dec. 2021, doi: 10.3390/app112411910.
- [4] S. C. Altıparmak and B. Xiao, “A market assessment of additive manufacturing potential for the aerospace industry,” *J Manuf Process*, vol. 68, pp. 728–738, Aug. 2021, doi: 10.1016/j.jmapro.2021.05.072.
- [5] S. Rouf *et al.*, “Additive manufacturing technologies: Industrial and medical applications,” *Sustainable Operations and Computers*, vol. 3, pp. 258–274, 2022, doi: 10.1016/j.susoc.2022.05.001.
- [6] G. N. Tiwari and L. Sahota, *Advanced solar-distillation systems: basic principles, thermal modeling, and its application*. Springer, 2017.
- [7] F. A. Essa, “Thermal desalination systems: from traditionality to modernity and development,” *Distillation Processes-From Conventional to Reactive Distillation Modeling, Simulation and Optimization*. London: IntechOpen, p. 23, 2022.
- [8] S. M. J. Seyed Sabour and B. Ghorashi, “A comprehensive review of major water desalination techniques and mineral extraction from saline water,” *Sep Purif Technol*, vol. 349, p. 127913, Dec. 2024, doi: 10.1016/j.seppur.2024.127913.
- [9] J. J. Koh *et al.*, “Robust, 3D-printed hydratable plastics for effective solar desalination,” *Nano Energy*, vol. 79, p. 105436, Jan. 2021, doi: 10.1016/j.nanoen.2020.105436.

- [10] N. Cao *et al.*, “A self-regenerating air-laid paper wrapped ASA 3D cone-shaped Janus evaporator for efficient and stable solar desalination,” *Chemical Engineering Journal*, vol. 397, p. 125522, Oct. 2020, doi: 10.1016/j.cej.2020.125522.
- [11] A. K. Kaviti, A. Siva Ram, A. Aruna Kumari, and S. Hussain, “Development of hierarchical structures for enhanced solar desalination,” *Mater Today Proc*, vol. 44, pp. 315–320, 2021, doi: 10.1016/j.matpr.2020.09.473.
- [12] A. Jimeno-Morenilla, P. Azariadis, R. Molina-Carmona, S. Kyratzi, and V. Moulitanitis, “Technology enablers for the implementation of Industry 4.0 to traditional manufacturing sectors: A review,” *Comput Ind*, vol. 125, p. 103390, Feb. 2021, doi: 10.1016/j.compind.2020.103390.
- [13] A. Thompson, “Surface texture measurement of metal additively manufactured parts by X-ray computed tomography,” PhD thesis, University of Nottingham, 2019.
- [14] S. A. M. Tofail, E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. O’Donoghue, and C. Charitidis, “Additive manufacturing: scientific and technological challenges, market uptake and opportunities,” *Materials Today*, vol. 21, no. 1, pp. 22–37, Jan. 2018, doi: 10.1016/j.mattod.2017.07.001.
- [15] B. Blakey-Milner *et al.*, “Metal additive manufacturing in aerospace: A review,” *Mater Des*, vol. 209, p. 110008, Nov. 2021, doi: 10.1016/j.matdes.2021.110008.
- [16] S. Salifu, D. Desai, O. Ogunbiyi, and K. Mwale, “Recent development in the additive manufacturing of polymer-based composites for automotive structures—a review,” *The International Journal of Advanced Manufacturing Technology*, vol. 119, no. 11–12, pp. 6877–6891, Apr. 2022, doi: 10.1007/s00170-021-08569-z.
- [17] B. Sun, Q. Ma, X. Wang, J. Liu, and M. R. M. Rejab, “Additive manufacturing in medical applications: A brief review,” *IOP Conf Ser Mater Sci Eng*, vol. 1078, no. 1, p. 012007, Feb. 2021, doi: 10.1088/1757-899X/1078/1/012007.
- [18] S. Halassi, J. Semeijn, and N. Kiratli, “From consumer to prosumer: a supply chain revolution in 3D printing,” *International Journal of Physical*

Distribution & Logistics Management, vol. 49, no. 2, pp. 200–216, Mar. 2019, doi: 10.1108/IJPDLM-03-2018-0139.

- [19] A. Razavykia, E. Brusa, C. Delprete, and R. Yavari, “An Overview of Additive Manufacturing Technologies—A Review to Technical Synthesis in Numerical Study of Selective Laser Melting,” *Materials*, vol. 13, no. 17, p. 3895, Sep. 2020, doi: 10.3390/ma13173895.
- [20] K. Ko, S. Jin, S. E. Lee, and J.-W. Hong, “Impact resistance of nacre-like composites diversely patterned by 3D printing,” *Compos Struct*, vol. 238, p. 111951, Apr. 2020, doi: 10.1016/j.compstruct.2020.111951.
- [21] A. R. Studart, “Additive manufacturing of biologically-inspired materials,” *Chem Soc Rev*, vol. 45, no. 2, pp. 359–376, 2016, doi: 10.1039/C5CS00836K.
- [22] S. J. Trenfield, C. M. Madla, A. W. Basit, and S. Gaisford, “Binder Jet Printing in Pharmaceutical Manufacturing,” in *3D Printing of Pharmaceuticals*, vol. 31, AAPS Advances in the Pharmaceutical Sciences Series, 2018, ch. 1, pp. 41–54. doi: 10.1007/978-3-319-90755-0_3.
- [23] S. H. Siddique, P. J. Hazell, H. Wang, J. P. Escobedo, and A. A. H. Ameri, “Lessons from nature: 3D printed bio-inspired porous structures for impact energy absorption – A review,” *Addit Manuf*, vol. 58, p. 103051, Oct. 2022, doi: 10.1016/j.addma.2022.103051.
- [24] P. Robles Martinez, A. W. Basit, and S. Gaisford, “The History, Developments and Opportunities of Stereolithography,” in *3D Printing of Pharmaceuticals*, vol. 31, A. W. Basit and S. Gaisford, Eds., Cham: AAPS Advances in the Pharmaceutical Sciences Series, 2018, ch. 2, pp. 55–79. doi: 10.1007/978-3-319-90755-0_4.
- [25] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui, “Additive manufacturing (3D printing): A review of materials, methods, applications and challenges,” *Compos B Eng*, vol. 143, pp. 172–196, Jun. 2018, doi: 10.1016/j.compositesb.2018.02.012.
- [26] F. Fina, A. Goyanes, S. Gaisford, and A. W. Basit, “Selective laser sintering (SLS) 3D printing of medicines,” *Int J Pharm*, vol. 529, no. 1–2, pp. 285–293, Aug. 2017, doi: 10.1016/j.ijpharm.2017.06.082.
- [27] B. Utela, D. Storti, R. Anderson, and M. Ganter, “A review of process development steps for new material systems in three dimensional printing

- (3DP),” *J Manuf Process*, vol. 10, no. 2, pp. 96–104, Jul. 2008, doi: 10.1016/j.jmapro.2009.03.002.
- [28] D. R. Jones *et al.*, “Spall fracture in additive manufactured Ti-6Al-4V,” *J Appl Phys*, vol. 120, no. 13, Oct. 2016, doi: 10.1063/1.4963279.
- [29] M. Sireesha, J. Lee, A. S. Kranthi Kiran, V. J. Babu, B. B. T. Kee, and S. Ramakrishna, “A review on additive manufacturing and its way into the oil and gas industry,” *RSC Adv*, vol. 8, no. 40, pp. 22460–22468, 2018, doi: 10.1039/C8RA03194K.
- [30] M. Vaezi, P. Drescher, and H. Seitz, “Beamless Metal Additive Manufacturing,” *Materials*, vol. 13, no. 4, p. 922, Feb. 2020, doi: 10.3390/ma13040922.
- [31] N. Guo and M. C. Leu, “Additive manufacturing: technology, applications and research needs,” *Frontiers of Mechanical Engineering*, vol. 8, no. 3, pp. 215–243, Sep. 2013, doi: 10.1007/s11465-013-0248-8.
- [32] J. Frketic, T. Dickens, and S. Ramakrishnan, “Automated manufacturing and processing of fiber-reinforced polymer (FRP) composites: An additive review of contemporary and modern techniques for advanced materials manufacturing,” *Addit Manuf*, vol. 14, pp. 69–86, Mar. 2017, doi: 10.1016/j.addma.2017.01.003.
- [33] V. Kumar, H. Kaur, A. Kumari, G. Hooda, V. Garg, and H. Dureja, “Drug delivery and testing via 3D printing,” *Bioprinting*, vol. 36, p. e00298, Dec. 2023, doi: 10.1016/j.bprint.2023.e00298.
- [34] H. A. Alshahrani, “Review of 4D printing materials and reinforced composites: Behaviors, applications and challenges,” *Journal of Science: Advanced Materials and Devices*, vol. 6, no. 2, pp. 167–185, Jun. 2021, doi: 10.1016/j.jsamd.2021.03.006.
- [35] M. Srivastava, S. Rathee, V. Patel, A. Kumar, and P. G. Koppad, “A review of various materials for additive manufacturing: Recent trends and processing issues,” *Journal of Materials Research and Technology*, vol. 21, pp. 2612–2641, Nov. 2022, doi: 10.1016/j.jmrt.2022.10.015.
- [36] V. B. Vukkum and R. K. Gupta, “Review on corrosion performance of laser powder-bed fusion printed 316L stainless steel: Effect of processing parameters, manufacturing defects, post-processing, feedstock, and microstructure,” *Mater Des*, vol. 221, p. 110874, Sep. 2022, doi: 10.1016/j.matdes.2022.110874.

- [37] M. Srivastava, S. Rathee, A. Tiwari, and M. Dongre, “Wire arc additive manufacturing of metals: A review on processes, materials and their behaviour,” *Mater Chem Phys*, vol. 294, p. 126988, Jan. 2023, doi: 10.1016/j.matchemphys.2022.126988.
- [38] S. Park and K. (Kelvin) Fu, “Polymer-based filament feedstock for additive manufacturing,” *Compos Sci Technol*, vol. 213, p. 108876, Sep. 2021, doi: 10.1016/j.compscitech.2021.108876.
- [39] N. K. Bankapalli, V. Gupta, P. Saxena, A. Bajpai, C. Lahoda, and J. Polte, “Filament fabrication and subsequent additive manufacturing, debinding, and sintering for extrusion-based metal additive manufacturing and their applications: A review,” *Compos B Eng*, vol. 264, p. 110915, Sep. 2023, doi: 10.1016/j.compositesb.2023.110915.
- [40] V. Kishore and A. A. Hassen, “Polymer and composites additive manufacturing,” in *Additive Manufacturing*, Elsevier, 2021, pp. 183–216. doi: 10.1016/B978-0-12-818411-0.00021-5.
- [41] I. Gibson, D. Rosen, B. Stucker, and M. Khorasani, *Additive Manufacturing Technologies*. Cham: Springer International Publishing, 2021. doi: 10.1007/978-3-030-56127-7.
- [42] J. R. C. Dizon, A. H. Espera, Q. Chen, and R. C. Advincula, “Mechanical characterization of 3D-printed polymers,” *Addit Manuf*, vol. 20, pp. 44–67, Mar. 2018, doi: 10.1016/j.addma.2017.12.002.
- [43] A. Alafaghani, A. Qattawi, B. Alrawi, and A. Guzman, “Experimental Optimization of Fused Deposition Modelling Processing Parameters: A Design-for-Manufacturing Approach,” *Procedia Manuf*, vol. 10, pp. 791–803, 2017, doi: 10.1016/j.promfg.2017.07.079.
- [44] D. Popescu, A. Zapciu, C. Amza, F. Baci, and R. Marinescu, “FDM process parameters influence over the mechanical properties of polymer specimens: A review,” *Polym Test*, vol. 69, pp. 157–166, Aug. 2018, doi: 10.1016/j.polymertesting.2018.05.020.
- [45] A. Dey, I. N. Roan Eagle, and N. Yodo, “A Review on Filament Materials for Fused Filament Fabrication,” *Journal of Manufacturing and Materials Processing*, vol. 5, no. 3, p. 69, Jun. 2021, doi: 10.3390/jmmp5030069.
- [46] S. Olivera, H. B. Muralidhara, K. Venkatesh, K. Gopalakrishna, and C. S. Vivek, “Plating on acrylonitrile–butadiene–styrene (ABS) plastic: a

- review,” *J Mater Sci*, vol. 51, no. 8, pp. 3657–3674, Apr. 2016, doi: 10.1007/s10853-015-9668-7.
- [47] Z. Liu, Y. Wang, B. Wu, C. Cui, Y. Guo, and C. Yan, “A critical review of fused deposition modeling 3D printing technology in manufacturing polylactic acid parts,” *The International Journal of Advanced Manufacturing Technology*, vol. 102, no. 9–12, pp. 2877–2889, Jun. 2019, doi: 10.1007/s00170-019-03332-x.
- [48] M. T. Sepahi, H. Abusalma, V. Jovanovic, and H. Eisazadeh, “Mechanical Properties of 3D-Printed Parts Made of Polyethylene Terephthalate Glycol,” *J Mater Eng Perform*, vol. 30, no. 9, pp. 6851–6861, Sep. 2021, doi: 10.1007/s11665-021-06032-4.
- [49] M. Ramesh and K. Panneerselvam, “Mechanical investigation and optimization of parameter selection for Nylon material processed by FDM,” *Mater Today Proc*, vol. 46, pp. 9303–9307, 2021, doi: 10.1016/j.matpr.2020.02.697.
- [50] S. Kumar *et al.*, “Solar stills: A review for water scarcity solutions,” *Heliyon*, vol. 10, no. 19, p. e38751, Oct. 2024, doi: 10.1016/j.heliyon.2024.e38751.
- [51] V. Shrivastava and A. Kumar, “Embodied energy analysis of the indirect solar drying unit,” *International Journal of Ambient Energy*, vol. 38, no. 3, pp. 280–285, Apr. 2017, doi: 10.1080/01430750.2015.1092471.
- [52] M. K. Gaur and G. N. Tiwari, “Optimization of number of collectors for integrated PV/T hybrid active solar still,” *Appl Energy*, vol. 87, no. 5, pp. 1763–1772, May 2010, doi: 10.1016/j.apenergy.2009.10.019.
- [53] B. Mishra, P. Kumar, C. Saraswat, S. Chakraborty, and A. Gautam, “Water Security in a Changing Environment: Concept, Challenges and Solutions,” *Water (Basel)*, vol. 13, no. 4, p. 490, Feb. 2021, doi: 10.3390/w13040490.
- [54] V. Sivakumar and E. Ganapathy Sundaram, “Improvement techniques of solar still efficiency: A review,” *Renewable and Sustainable Energy Reviews*, vol. 28, pp. 246–264, Dec. 2013, doi: 10.1016/j.rser.2013.07.037.
- [55] A. Maurya, R. Kumar, A. Gupta, M. H. Ahmadi, and M. Al-Bahrani, “Energy, exergy, economic, exergoeconomic, exergoenvironment, and enviroeconomic (6E) analysis of solar stills—A critical review,” *Energy Sci Eng*, vol. 12, no. 1, pp. 267–283, Jan. 2024, doi: 10.1002/ese3.1613.

- [56] B. B. Ashoor, S. Mansour, A. Giwa, V. Dufour, and S. W. Hasan, "Principles and applications of direct contact membrane distillation (DCMD): A comprehensive review," *Desalination*, vol. 398, pp. 222–246, Nov. 2016, doi: 10.1016/j.desal.2016.07.043.
- [57] A.-S. Jönsson, R. Wimmerstedt, and A.-C. Harrysson, "Membrane distillation - a theoretical study of evaporation through microporous membranes," *Desalination*, vol. 56, pp. 237–249, Jan. 1985, doi: 10.1016/0011-9164(85)85028-1.
- [58] A. Panagopoulos, K.-J. Haralambous, and M. Loizidou, "Desalination brine disposal methods and treatment technologies - A review," *Science of The Total Environment*, vol. 693, p. 133545, Nov. 2019, doi: 10.1016/j.scitotenv.2019.07.351.
- [59] L. Eykens, T. Reyns, K. De Sitter, C. Dotremont, L. Pinoy, and B. Van der Bruggen, "How to select a membrane distillation configuration? Process conditions and membrane influence unraveled," *Desalination*, vol. 399, pp. 105–115, Dec. 2016, doi: 10.1016/j.desal.2016.08.019.
- [60] A. M. Karam, A. S. Alsaadi, N. Ghaffour, and T. M. Laleg-Kirati, "Analysis of direct contact membrane distillation based on a lumped-parameter dynamic predictive model," *Desalination*, vol. 402, pp. 50–61, Jan. 2017, doi: 10.1016/j.desal.2016.09.002.
- [61] A. A. Sonin and R. F. Probstein, "A hydrodynamic theory of desalination by electrodialysis," *Desalination*, vol. 5, no. 3, pp. 293–329, 1968, doi: 10.1016/S0011-9164(00)80105-8.
- [62] K. Tado, F. Sakai, Y. Sano, and A. Nakayama, "An analysis on ion transport process in electrodialysis desalination," *Desalination*, vol. 378, pp. 60–66, Jan. 2016, doi: 10.1016/j.desal.2015.10.001.
- [63] B. A. Qureshi and S. M. Zubair, "Exergy and sensitivity analysis of electrodialysis reversal desalination plants," *Desalination*, vol. 394, pp. 195–203, Sep. 2016, doi: 10.1016/j.desal.2016.05.015.
- [64] M. Asraf-Snir, J. Gilron, and Y. Oren, "Gypsum scaling of anion exchange membranes in electrodialysis," *J Memb Sci*, vol. 520, pp. 176–186, Dec. 2016, doi: 10.1016/j.memsci.2016.07.013.
- [65] D. R. Paul, "The role of membrane pressure in reverse osmosis," *J Appl Polym Sci*, vol. 16, no. 3, pp. 771–782, Mar. 1972, doi: 10.1002/app.1972.070160320.

- [66] M. K. Gnanadason, P. S. Kumar, V. H. Wilson, G. Hariharan, and N. S. Vinayagamoorthi, "Design and Performance Analysis of an Innovative Single Basin Solar NanoStill," *Smart Grid and Renewable Energy*, vol. 04, no. 01, pp. 88–98, 2013, doi: 10.4236/sgre.2013.41012.
- [67] H. Thakkar, A. Sankhala, P. V Ramana, and H. Panchal, "A detailed review on solar desalination techniques," *International Journal of Ambient Energy*, vol. 41, no. 9, pp. 1066–1087, Jul. 2020, doi: 10.1080/01430750.2018.1490351.
- [68] M. K. Gnanadason, P. S. Kumar, S. Rajakumar, and M. H. S. Yousuf, "Effect of nanofluids in a vacuum single basin solar still," *International Journal of Advanced Engineering Research and Studies*, vol. 1, pp. 171–177, 2011.
- [69] M. F. Yusof *et al.*, "Investigation on the Urban Grey Water Treatment Using a Cost-Effective Solar Distillation Still," *Sustainability*, vol. 14, no. 15, p. 9452, Aug. 2022, doi: 10.3390/su14159452.
- [70] G. N. Tiwari, S. K. Shukla, and I. P. Singh, "Computer modeling of passive/active solar stills by using inner glass temperature," *Desalination*, vol. 154, no. 2, pp. 171–185, Apr. 2003, doi: 10.1016/S0011-9164(03)80018-8.
- [71] M. Shinde, R. Navthar, and S. M. Shinde, "Review on the types of solar stills," *International Journal of Ambient Energy*, vol. 43, no. 1, pp. 1420–1428, Dec. 2022, doi: 10.1080/01430750.2019.1707114.
- [72] G. N. Tiwari, V. Dimri, U. Singh, A. Chel, and B. Sarkar, "Comparative thermal performance evaluation of an active solar distillation system," *Int J Energy Res*, vol. 31, no. 15, pp. 1465–1482, Dec. 2007, doi: 10.1002/er.1314.
- [73] A.-J. N. Khalifa, A. S. Al-Jubouri, and M. K. Abed, "An experimental study on modified simple solar stills," *Energy Convers Manag*, vol. 40, no. 17, pp. 1835–1847, Nov. 1999, doi: 10.1016/S0196-8904(99)00049-7.
- [74] M. Boukar and A. Harmim, "Effect of climatic conditions on the performance of a simple basin solar still: a comparative study," *Desalination*, vol. 137, no. 1–3, pp. 15–22, May 2001, doi: 10.1016/S0011-9164(01)00199-0.

- [75] S. Yadav and K. Sudhakar, "Different domestic designs of solar stills: A review," *Renewable and Sustainable Energy Reviews*, vol. 47, pp. 718–731, Jul. 2015, doi: 10.1016/j.rser.2015.03.064.
- [76] A. A. El-Sebaili, M. R. I. Ramadan, S. Aboul-Enein, and N. Salem, "Thermal performance of a single-basin solar still integrated with a shallow solar pond," *Energy Convers Manag*, vol. 49, no. 10, pp. 2839–2848, Oct. 2008, doi: 10.1016/j.enconman.2008.03.002.
- [77] S. Shanmugan *et al.*, "A technical appraisal of solar photovoltaic-integrated single slope single basin solar still for simultaneous energy and water generation," *Case Studies in Thermal Engineering*, vol. 54, p. 104032, Feb. 2024, doi: 10.1016/j.csite.2024.104032.
- [78] T. Elango and K. Kalidasa Murugavel, "The effect of the water depth on the productivity for single and double basin double slope glass solar stills," *Desalination*, vol. 359, pp. 82–91, Mar. 2015, doi: 10.1016/j.desal.2014.12.036.
- [79] K. Kalidasa Murugavel and K. Srithar, "Performance study on basin type double slope solar still with different wick materials and minimum mass of water," *Renew Energy*, vol. 36, no. 2, pp. 612–620, Feb. 2011, doi: 10.1016/j.renene.2010.08.009.
- [80] M. S. Sodha, J. K. Nayak, G. N. Tiwari, and A. Kumar, "Double basin solar still," *Energy Convers Manag*, vol. 20, no. 1, pp. 23–32, Jan. 1980, doi: 10.1016/0196-8904(80)90025-4.
- [81] M. E. Murad, W. H. Alawee, and H. A. Dhahad, "Advanced techniques for augmenting the performance of double-slope solar stills: A comparative study," *Desalination Water Treat*, vol. 320, p. 100581, Oct. 2024, doi: 10.1016/j.dwt.2024.100581.
- [82] A. R. Nadgire, S. B. Barve, and P. K. Ithape, "Experimental Investigation and Performance Analysis of Double-Basin Solar Still Using CFD Techniques," *Journal of The Institution of Engineers (India): Series C*, vol. 101, no. 3, pp. 531–539, Jun. 2020, doi: 10.1007/s40032-020-00561-y.
- [83] Y. Taamneh and M. M. Taamneh, "Performance of pyramid-shaped solar still: Experimental study," *Desalination*, vol. 291, pp. 65–68, Apr. 2012, doi: 10.1016/j.desal.2012.01.026.

- [84] R. Sathyamurthy, H. J. Kennady, P. K. Nagarajan, and A. Ahsan, "Factors affecting the performance of triangular pyramid solar still," *Desalination*, vol. 344, pp. 383–390, Jul. 2014, doi: 10.1016/j.desal.2014.04.005.
- [85] G. N. Tiwari and A. Kumar, "Nocturnal water production by tubular solar stills using waste heat to preheat brine," *Desalination*, vol. 69, no. 3, pp. 309–318, Jan. 1988, doi: 10.1016/0011-9164(88)80032-8.
- [86] Kh. Md. S. Islam and T. Fukuhara, "Production Analysis of a Tubular Solar Still," *Doboku Gakkai Ronbunshuu B*, vol. 63, no. 2, pp. 108–119, 2007, doi: 10.2208/jscejb.63.108.
- [87] I. Alatawi, A. Khaliq, A. M. Ahmed Heniegal, G. B. Abdelaziz, and M. Elashmawy, "Tubular solar stills: Recent developments and future," *Solar Energy Materials and Solar Cells*, vol. 242, p. 111785, Aug. 2022, doi: 10.1016/j.solmat.2022.111785.
- [88] A. Ahsan, "Production Model of New Tubular Solar Still and Its Productivity Characteristics," PhD thesis, University of Fukui, 2009.
- [89] B. I. Ismail, "Design and performance of a transportable hemispherical solar still," *Renew Energy*, vol. 34, no. 1, pp. 145–150, Jan. 2009, doi: 10.1016/j.renene.2008.03.013.
- [90] W. A. A. Al-wahid, H. A. K. Saad, Z. H. Hasan, and K. Sopian, "Experimental study of the performance of hemispherical solar still with optimum value of rocks as heat transfer enhancers," *AIMS Energy*, vol. 10, no. 4, pp. 885–899, 2022, doi: 10.3934/energy.2022040.
- [91] B. S. Kumar, S. Kumar, and R. Jayaprakash, "Performance analysis of a 'V' type solar still using a charcoal absorber and a boosting mirror," *Desalination*, vol. 229, no. 1–3, pp. 217–230, Sep. 2008, doi: 10.1016/j.desal.2007.09.009.
- [92] A. A. Kiran, P. V. Sivashankar, P. U. Suneesh, and D. C. Denkenberger, "V-Type solar still integrated with hybrid solar concentrator," *Cogent Eng*, vol. 9, no. 1, Dec. 2022, doi: 10.1080/23311916.2022.2073650.
- [93] N. K. Dhiman, "Transient analysis of a spherical solar still," *Desalination*, vol. 69, no. 1, pp. 47–55, Jan. 1988, doi: 10.1016/0011-9164(88)80005-5.
- [94] K. V. Modi, K. H. Nayi, and S. S. Sharma, "Influence of water mass on the performance of spherical basin solar still integrated with parabolic

- reflector,” *Groundw Sustain Dev*, vol. 10, p. 100299, Apr. 2020, doi: 10.1016/j.gsd.2019.100299.
- [95] G. N. Tiwari and L. Sahota, “History of Passive Solar-Distillation Systems,” in *Advanced Solar-Distillation Systems: Basic Principles, Thermal Modeling, and Its Application*, G. N. Tiwari and L. Sahota, Eds., Singapore: Springer Singapore, 2017, pp. 121–155. doi: 10.1007/978-981-10-4672-8_3.
- [96] A. E. Kabeel, “Performance of solar still with a concave wick evaporation surface,” *Energy*, vol. 34, no. 10, pp. 1504–1509, Oct. 2009, doi: 10.1016/j.energy.2009.06.050.
- [97] H. Tanaka, “Tilted wick solar still with flat plate bottom reflector,” *Desalination*, vol. 273, no. 2–3, pp. 405–413, Jun. 2011, doi: 10.1016/j.desal.2011.01.073.
- [98] J. T. Mahdi, B. E. Smith, and A. O. Sharif, “An experimental wick-type solar still system: Design and construction,” *Desalination*, vol. 267, no. 2–3, pp. 233–238, Feb. 2011, doi: 10.1016/j.desal.2010.09.032.
- [99] R. S. Hansen, C. S. Narayanan, and K. K. Murugavel, “Performance analysis on inclined solar still with different new wick materials and wire mesh,” *Desalination*, vol. 358, pp. 1–8, Feb. 2015, doi: 10.1016/j.desal.2014.12.006.
- [100] S. Kalogirou, “Use of parabolic trough solar energy collectors for sea-water desalination,” *Appl Energy*, vol. 60, no. 2, pp. 65–88, Jun. 1998, doi: 10.1016/S0306-2619(98)00018-X.
- [101] M. Gowtham, M. S. Chander, K. V. S. S. Mallikarujanan, and N. Karthikeyan, “Concentrated Parabolic Solar Distiller with latent heat storage capacity,” *International Journal of Chemical Engineering and Applications*, vol. 2, no. 3, p. 185, 2011.
- [102] W. Fuqiang, C. Ziming, T. Jianyu, Y. Yuan, S. Yong, and L. Linhua, “Progress in concentrated solar power technology with parabolic trough collector system: A comprehensive review,” *Renewable and Sustainable Energy Reviews*, vol. 79, pp. 1314–1328, Nov. 2017, doi: 10.1016/j.rser.2017.05.174.
- [103] M. Abdelkader, A. S. Nafy, A. Abdelmotalip, and A. A. Mabrouk, “Experimental evaluation of solar still mathematical models,” in *Proceedings of the Fourth International Water Technology Conference, Alexandria, Egypt*, Citeseer, 1999, pp. 23–25.

- [104] A. S. Nafey, M. Abdelkader, A. Abdelmotalip, and A. A. Mabrouk, "Parameters affecting solar still productivity," *Energy Convers Manag*, vol. 41, no. 16, pp. 1797–1809, Nov. 2000, doi: 10.1016/S0196-8904(99)00188-0.
- [105] E. A. Almuhanha, "Evaluation of Single Slope Solar Still Integrated With Evaporative Cooling System for Brackish Water Desalination," *Journal of Agricultural Science*, vol. 6, no. 1, Dec. 2013, doi: 10.5539/jas.v6n1p48.
- [106] H. Aburideh, A. Deliou, B. Abbad, F. Alaoui, D. Tassalit, and Z. Tigrine, "An Experimental Study of a Solar Still: Application on the sea water desalination of Fouka," *Procedia Eng*, vol. 33, pp. 475–484, 2012, doi: 10.1016/j.proeng.2012.01.1227.
- [107] R. N. Morse and W. R. W. Read, "A rational basis for the engineering development of a solar still," *Solar Energy*, vol. 12, no. 1, pp. 5–17, Sep. 1968, doi: 10.1016/0038-092X(68)90021-2.
- [108] N. Rahbar and J. A. Esfahani, "Experimental study of a novel portable solar still by utilizing the heatpipe and thermoelectric module," *Desalination*, vol. 284, pp. 55–61, Jan. 2012, doi: 10.1016/j.desal.2011.08.036.
- [109] C. E. Okeke, S. U. Egarievwe, and A. O. E. Animalu, "Effects of coal and charcoal on solar-still performance," *Energy*, vol. 15, no. 11, pp. 1071–1073, Nov. 1990, doi: 10.1016/0360-5442(90)90035-Z.
- [110] W. A. Kamal, "A theoretical and experimental study of the basin-type solar still under the arabian gulf climatic conditions," *Solar & Wind Technology*, vol. 5, no. 2, pp. 147–157, Jan. 1988, doi: 10.1016/0741-983X(88)90074-4.
- [111] F. A. Essa *et al.*, "Parameters Affecting the Efficiency of Solar Stills—Recent Review," *Sustainability*, vol. 14, no. 17, p. 10668, Aug. 2022, doi: 10.3390/su141710668.
- [112] H. Al-Hinai, M. S. Al-Nassri, and B. A. Jubran, "Effect of climatic, design and operational parameters on the yield of a simple solar still," *Energy Convers Manag*, vol. 43, no. 13, pp. 1639–1650, Sep. 2002, doi: 10.1016/S0196-8904(01)00120-0.
- [113] M. A. S. Malik, G. N. Tiwari, A. Kumar, and M. S. Sodha, *Solar distillation (a practical study of a wide range of stills and their optimum design, construction, and performance)*. U.S. Department of Energy, 1982.

- [114] T. Alheefi, “Experimental and Analytical Study of Water Production of Solar Still,” Brunel University London, Uxbridge, UK, 2019.
- [115] B. Koffi *et al.*, “Modelling of Solar Still for Production of Pure Water in the Abidjan Zones,” *Research Journal of Physics*, vol. 3, pp. 5–13, Jan. 2009, doi: 10.3923/rjp.2009.5.13.
- [116] M. S. S. Abujazar, S. Fatihah, A. R. Rakmi, and M. Z. Shahrom, “The effects of design parameters on productivity performance of a solar still for seawater desalination: A review,” *Desalination*, vol. 385, pp. 178–193, May 2016, doi: 10.1016/j.desal.2016.02.025.
- [117] M. Mohsenzadeh, L. Aye, and P. Christopher, “Effect of humidity level and aspect ratio on convective heat transfer coefficient and water productivity of a solar still: Experimental and theoretical analysis,” *Appl Therm Eng*, vol. 228, p. 120547, Jun. 2023, doi: 10.1016/j.applthermaleng.2023.120547.
- [118] F. A. Essa, A. S. Abdullah, and Z. M. Omara, “Rotating discs solar still: New mechanism of desalination,” *J Clean Prod*, vol. 275, p. 123200, Dec. 2020, doi: 10.1016/j.jclepro.2020.123200.
- [119] S. H. Soliman, “Effect of wind on solar distillation,” *Solar Energy*, vol. 13, no. 4, pp. 403–415, Jul. 1972, doi: 10.1016/0038-092X(72)90006-0.
- [120] A. A. El-Sebaili, “Effect of wind speed on active and passive solar stills,” *Energy Convers Manag*, vol. 45, no. 7–8, pp. 1187–1204, May 2004, doi: 10.1016/j.enconman.2003.09.036.
- [121] A. J. Khalifa and M. Ali, “Indoor tests on the effect of wind speed on still performance,” *International Journal of Energy and Environment*, vol. 6, pp. 299–308, Apr. 2015.
- [122] R. M. Reddy and K. H. Reddy, “Upward heat flow analysis in basin type solar still,” *Journal of Mining and Metallurgy B: Metallurgy*, vol. 45, no. 1, pp. 121–126, 2009.
- [123] A. A. El-Sebaili, M. R. I. Ramadan, S. Aboul-Enein, and M. El-Naggar, “Effect of fin configuration parameters on single basin solar still performance,” *Desalination*, vol. 365, pp. 15–24, Jun. 2015, doi: 10.1016/j.desal.2015.02.002.
- [124] A. Kr. Tiwari and G. N. Tiwari, “Effect of water depths on heat and mass transfer in a passive solar still: in summer climatic condition,” *Desalination*, vol. 195, no. 1–3, pp. 78–94, Aug. 2006, doi: 10.1016/j.desal.2005.11.014.

- [125] M. K. Phadatare and S. K. Verma, "Influence of water depth on internal heat and mass transfer in a plastic solar still," *Desalination*, vol. 217, no. 1–3, pp. 267–275, Nov. 2007, doi: 10.1016/j.desal.2007.03.006.
- [126] S. S. S. Al-Mezeini *et al.*, "Design and Experimental Studies on a Single Slope Solar Still for Water Desalination," *Water (Basel)*, vol. 15, no. 4, p. 704, Feb. 2023, doi: 10.3390/w15040704.
- [127] A. Ahsan, M. Imteaz, U. A. Thomas, M. Azmi, A. Rahman, and N. N. Nik Daud, "Parameters affecting the performance of a low cost solar still," *Appl Energy*, vol. 114, pp. 924–930, Feb. 2014, doi: 10.1016/j.apenergy.2013.08.066.
- [128] A. Muthu Manokar, K. Kalidasa Murugavel, and G. Esakkimuthu, "Different parameters affecting the rate of evaporation and condensation on passive solar still – A review," *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 309–322, Oct. 2014, doi: 10.1016/j.rser.2014.05.092.
- [129] S. Suneja and G. N. Tiwari, "Effect of water depth on the performance of an inverted absorber double basin solar still," *Energy Convers Manag*, vol. 40, no. 17, pp. 1885–1897, Nov. 1999, doi: 10.1016/S0196-8904(99)00047-3.
- [130] M. Ali Samee, U. K. Mirza, T. Majeed, and N. Ahmad, "Design and performance of a simple single basin solar still," *Renewable and Sustainable Energy Reviews*, vol. 11, no. 3, pp. 543–549, Apr. 2007, doi: 10.1016/j.rser.2005.03.003.
- [131] A. J. N. Khalifa and A. M. Hamood, "On the verification of the effect of water depth on the performance of basin type solar stills," *Solar Energy*, vol. 83, no. 8, pp. 1312–1321, Aug. 2009, doi: 10.1016/j.solener.2009.04.006.
- [132] Ali. F. Muftah, M. A. Alghoul, A. Fudholi, M. M. Abdul-Majeed, and K. Sopian, "Factors affecting basin type solar still productivity: A detailed review," *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 430–447, Apr. 2014, doi: 10.1016/j.rser.2013.12.052.
- [133] A. A. Hegazy, "Effect of dust accumulation on solar transmittance through glass covers of plate-type collectors," *Renew Energy*, vol. 22, no. 4, pp. 525–540, Apr. 2001, doi: 10.1016/S0960-1481(00)00093-8.
- [134] H. C. Hottel and B. B. Woertz, "The Performance of Flat-Plate Solar-Heat Collectors," *J Fluids Eng*, vol. 64, no. 2, pp. 91–103, Feb. 1942, doi: 10.1115/1.4018980.

- [135] A. M. El-Nashar, "The effect of dust accumulation on the performance of evacuated tube collectors," *Solar Energy*, vol. 53, no. 1, pp. 105–115, Jul. 1994, doi: 10.1016/S0038-092X(94)90610-6.
- [136] A. M. El-Nashar, "Seasonal effect of dust deposition on a field of evacuated tube collectors on the performance of a solar desalination plant," *Desalination*, vol. 239, no. 1–3, pp. 66–81, Apr. 2009, doi: 10.1016/j.desal.2008.03.007.
- [137] S. Jafari, M. Aghel, A. Sohani, and S. Hoseinzadeh, "Geographical Preference for Installation of Solar Still Water Desalination Technologies in Iran: An Analytical Hierarchy Process (AHP)-Based Answer," *Water (Basel)*, vol. 14, no. 2, p. 265, Jan. 2022, doi: 10.3390/w14020265.
- [138] Z. M. Omara, M. H. Hamed, and A. E. Kabeel, "Performance of finned and corrugated absorbers solar stills under Egyptian conditions," *Desalination*, vol. 277, no. 1–3, pp. 281–287, Aug. 2011, doi: 10.1016/j.desal.2011.04.042.
- [139] M. Sakthivel, S. Shanmugasundaram, and T. Alwarsamy, "An experimental study on a regenerative solar still with energy storage medium — Jute cloth," *Desalination*, vol. 264, no. 1–2, pp. 24–31, Dec. 2010, doi: 10.1016/j.desal.2010.06.074.
- [140] V. Velmurugan, S. Kumaran, N. Prabhu, and K. Srithar, "Productivity enhancement of stepped solar still: Performance analysis," *Thermal Science*, vol. 12, no. 3, pp. 153–163, 2008, doi: 10.2298/TSCI0803153V.
- [141] A. Ghoneyem and A. Ileri, "Software to analyze solar stills and an experimental study on the effects of the cover," *Desalination*, vol. 114, no. 1, pp. 37–44, Dec. 1997, doi: 10.1016/S0011-9164(97)00152-5.
- [142] B. A. Akash, M. S. Mohsen, and W. Nayfeh, "Experimental study of the basin type solar still under local climate conditions," *Energy Convers Manag*, vol. 41, no. 9, pp. 883–890, Jun. 2000, doi: 10.1016/S0196-8904(99)00158-2.
- [143] H. N. Singh and G. N. Tiwari, "Monthly performance of passive and active solar stills for different Indian climatic conditions," *Desalination*, vol. 168, pp. 145–150, Aug. 2004, doi: 10.1016/j.desal.2004.06.180.
- [144] S. N. Rai and G. N. Tiwari, "Single basin solar still coupled with flat plate collector," *Energy Convers Manag*, vol. 23, no. 3, pp. 145–149, Jan. 1983, doi: 10.1016/0196-8904(83)90057-2.

- [145] M. M. Morad, H. A. M. El-Maghawry, and K. I. Wasfy, "Improving the double slope solar still performance by using flat-plate solar collector and cooling glass cover," *Desalination*, vol. 373, pp. 1–9, Oct. 2015, doi: 10.1016/j.desal.2015.06.017.
- [146] S. Aboul-Enein, A. A. El-Sebaili, and E. El-Bialy, "Investigation of a single-basin solar still with deep basins," *Renew Energy*, vol. 14, no. 1–4, pp. 299–305, May 1998, doi: 10.1016/S0960-1481(98)00081-0.
- [147] H. P. Garg and H. S. Mann, "Effect of climatic, operational and design parameters on the year round performance of single-sloped and double-sloped solar still under Indian arid zone conditions," *Solar Energy*, vol. 18, no. 2, pp. 159–163, 1976, doi: 10.1016/0038-092X(76)90052-9.
- [148] B. B. Sahoo, N. Sahoo, P. Mahanta, L. Borbora, P. Kalita, and U. K. Saha, "Performance assessment of a solar still using blackened surface and thermocol insulation," *Renew Energy*, vol. 33, no. 7, pp. 1703–1708, Jul. 2008, doi: 10.1016/j.renene.2007.09.009.
- [149] B. K. Tariyal and A. H. Cherin, "Optical Fiber Communications," in *Encyclopedia of Physical Science and Technology*, Elsevier, 2003, pp. 271–294. doi: 10.1016/B0-12-227410-5/00521-4.
- [150] A. J. N. Khalifa and A. M. Hamood, "Effect of insulation thickness on the productivity of basin type solar stills: An experimental verification under local climate," *Energy Convers Manag*, vol. 50, no. 9, pp. 2457–2461, Sep. 2009, doi: 10.1016/j.enconman.2009.06.007.
- [151] E. T. L. Cöuras Ford, F. A. Ribeiro, R. V. Lima, and E. M. Souza, "Solar Distiller in a Pyramidal Covering and Isolation with Composite Material," *Revista de Engenharia Térmica*, vol. 7, no. 1, p. 37, Jun. 2008, doi: 10.5380/reterm.v7i1.61739.
- [152] H. Tanaka, "Monthly optimum inclination of glass cover and external reflector of a basin type solar still with internal and external reflector," *Solar Energy*, vol. 84, no. 11, pp. 1959–1966, Nov. 2010, doi: 10.1016/j.solener.2010.07.013.
- [153] M. A. Eltawil and Z. M. Omara, "Enhancing the solar still performance using solar photovoltaic, flat plate collector and hot air," *Desalination*, vol. 349, pp. 1–9, Sep. 2014, doi: 10.1016/j.desal.2014.06.021.
- [154] H. N. Panchal, "Enhancement of distillate output of double basin solar still with vacuum tubes," *Journal of King Saud University - Engineering*

Sciences, vol. 27, no. 2, pp. 170–175, Jul. 2015, doi:
10.1016/j.jksues.2013.06.007.

- [155] M. I. Ahmed, M. Hrairi, and A. F. Ismail, “On the characteristics of multistage evacuated solar distillation,” *Renew Energy*, vol. 34, no. 6, pp. 1471–1478, Jun. 2009, doi: 10.1016/j.renene.2008.10.029.
- [156] R. V. P. Patel and A. Kumar, “Experimental Investigation of Double Slope Solar Still for the Climatic Condition of Sultanpur,” *International Journal of Engineering and Technology*, vol. 9, no. 6, pp. 4019–4033, Dec. 2017, doi: 10.21817/ijet/2017/v9i6/170906309.
- [157] M. Abu-Arabi, Y. Zurigat, H. Al-Hinai, and S. Al-Hiddabi, “Modeling and performance analysis of a solar desalination unit with double-glass cover cooling,” *Desalination*, vol. 143, no. 2, pp. 173–182, May 2002, doi: 10.1016/S0011-9164(02)00238-2.
- [158] B. Janarthanan, J. Chandrasekaran, and S. Kumar, “Performance of floating cum tilted-wick type solar still with the effect of water flowing over the glass cover,” *Desalination*, vol. 190, no. 1–3, pp. 51–62, Apr. 2006, doi: 10.1016/j.desal.2005.08.005.
- [159] K. Kalidasa Murugavel, Kn. K. S. K. Chockalingam, and K. Srithar, “An experimental study on single basin double slope simulation solar still with thin layer of water in the basin,” *Desalination*, vol. 220, no. 1–3, pp. 687–693, Mar. 2008, doi: 10.1016/j.desal.2007.01.063.
- [160] K. Srithar, “Performance Analysis of Vapour Adsorption Solar Still Integrated with Mini-solar Pond for Effluent Treatment,” *International Journal of Chemical Engineering and Applications*, pp. 336–341, 2010, doi: 10.7763/IJCEA.2010.V1.58.
- [161] S. Abdallah, M. M. Abu-Khader, and O. Badran, “Effect of various absorbing materials on the thermal performance of solar stills,” *Desalination*, vol. 242, no. 1–3, pp. 128–137, Jun. 2009, doi: 10.1016/j.desal.2008.03.036.
- [162] J. Joseph, R. Saravanan, and S. Renganarayanan, “Studies on a single-stage solar desalination system for domestic applications,” *Desalination*, vol. 173, no. 1, pp. 77–82, Mar. 2005, doi: 10.1016/j.desal.2004.06.210.
- [163] S. A. Kalogirou, “Solar thermal collectors and applications,” *Prog Energy Combust Sci*, vol. 30, no. 3, pp. 231–295, 2004, doi: 10.1016/j.pecs.2004.02.001.

- [164] Y. A. Younes, D. A. Kospa, R. S. Salama, A. I. Ahmed, and A. A. Ibrahim, "Hydrophilic candle wastes microcapsules as a thermal energy storage material for all-day steam and electricity cogeneration," *Desalination*, vol. 550, p. 116377, Mar. 2023, doi: 10.1016/j.desal.2023.116377.
- [165] H. Nazir *et al.*, "Recent developments in phase change materials for energy storage applications: A review," *Int J Heat Mass Transf*, vol. 129, pp. 491–523, Feb. 2019, doi: 10.1016/j.ijheatmasstransfer.2018.09.126.
- [166] M. S. Sodha, A. Kumar, G. N. Tiwari, and G. C. Pandey, "Effects of dye on the performance of a solar still," *Appl Energy*, vol. 7, no. 1–3, pp. 147–162, Nov. 1980, doi: 10.1016/0306-2619(80)90055-0.
- [167] M. M. Naim and M. A. Abd El Kawi, "Non-conventional solar stills Part 1. Non-conventional solar stills with charcoal particles as absorber medium," *Desalination*, vol. 153, no. 1–3, pp. 55–64, Feb. 2003, doi: 10.1016/S0011-9164(02)01093-7.
- [168] G. M. Ayoub and L. Malaeb, "Developments in Solar Still Desalination Systems: A Critical Review," *Crit Rev Environ Sci Technol*, vol. 42, no. 19, pp. 2078–2112, Oct. 2012, doi: 10.1080/10643389.2011.574104.
- [169] M. A. Jamal, T. M. H. Junaidi, and J. A. Muaddi, "A step forward towards an ideal absorber for solar energy," *Int J Energy Res*, vol. 15, no. 5, pp. 367–375, Jul. 1991, doi: 10.1002/er.4440150504.
- [170] Ç. Tiris, M. Tiris, and İ. E. Türe, "Improvement of basin type solar still performance," *Renew Energy*, vol. 9, no. 1–4, pp. 758–761, Sep. 1996, doi: 10.1016/0960-1481(96)88394-7.
- [171] B. A. Akash, M. S. Mohsen, O. Osta, and Y. Elayan, "Experimental evaluation of a single-basin solar still using different absorbing materials," *Renew Energy*, vol. 14, no. 1–4, pp. 307–310, May 1998, doi: 10.1016/S0960-1481(98)00082-2.
- [172] A. S. Nafey, M. Abdelkader, A. Abdelmotalip, and A. A. Mabrouk, "Solar still productivity enhancement," *Energy Convers Manag*, vol. 42, no. 11, pp. 1401–1408, Jul. 2001, doi: 10.1016/S0196-8904(00)00107-2.
- [173] K. K. Gupta, P. K. S. Rathore, B. S. Sikarwar, and A. K. Pandey, "Solar to thermal energy storage performance of composite phase change material supported by copper foam loaded with graphite and boron nitride," *Solar Energy*, vol. 272, p. 112459, Apr. 2024, doi: 10.1016/j.solener.2024.112459.

- [174] K. Wang, Z. Qin, W. Tong, and C. Ji, "Thermal energy storage for solar energy utilization: Fundamentals and applications," *Resources, Challenges and Applications*, vol. 415, no. 9180410.5772, 2020.
- [175] N. Fadaei, A. Kasaeian, A. Akbarzadeh, and S. H. Hashemabadi, "Experimental investigation of solar chimney with phase change material (PCM)," *Renew Energy*, vol. 123, pp. 26–35, Aug. 2018, doi: 10.1016/j.renene.2018.01.122.
- [176] O. Mahian, S. Ghafarian, H. Sarrafha, A. Kasaeian, H. Yousefi, and W.-M. Yan, "Phase change materials in solar photovoltaics applied in buildings: An overview," *Solar Energy*, vol. 224, pp. 569–592, Aug. 2021, doi: 10.1016/j.solener.2021.06.010.
- [177] A. Kasaeian *et al.*, "A review on phase change materials in different types of solar stills," *J Energy Storage*, vol. 99, p. 113430, Oct. 2024, doi: 10.1016/j.est.2024.113430.
- [178] V. P. Katekar and S. S. Deshmukh, "A review of the use of phase change materials on performance of solar stills," *J Energy Storage*, vol. 30, p. 101398, Aug. 2020, doi: 10.1016/j.est.2020.101398.
- [179] M. Asbik, O. Ansari, A. Bah, N. Zari, A. Mimet, and H. El-Ghetany, "Exergy analysis of solar desalination still combined with heat storage system using phase change material (PCM)," *Desalination*, vol. 381, pp. 26–37, Mar. 2016, doi: 10.1016/j.desal.2015.11.031.
- [180] A. E. Kabeel, Y. A. F. El-Samadony, and W. M. El-Maghlany, "Comparative study on the solar still performance utilizing different PCM," *Desalination*, vol. 432, pp. 89–96, Apr. 2018, doi: 10.1016/j.desal.2018.01.016.
- [181] M. E.A.E. Ahmed, S. Abdo, M. A. Abdelrahman, and O. A. Gaheen, "Finned-encapsulated PCM pyramid solar still – Experimental study with economic analysis," *J Energy Storage*, vol. 73, p. 108908, Dec. 2023, doi: 10.1016/j.est.2023.108908.
- [182] A. S. Abdullah, Z. M. Omara, H. Ben Bacha, and M. M. Younes, "Employing convex shape absorber for enhancing the performance of solar still desalination system," *J Energy Storage*, vol. 47, p. 103573, Mar. 2022, doi: 10.1016/j.est.2021.103573.
- [183] M. Rousta, A. Kasaeian, A. Kouravand, G. Kasaeian, and M. A. Vaziri Rad, "Experimental investigation on tubular solar desalination using phase

- change material enhanced with nano-Co₃O₄ and aluminum shavings,” *Desalination*, vol. 567, p. 116972, Dec. 2023, doi: 10.1016/j.desal.2023.116972.
- [184] A. W. Kandeal *et al.*, “Improved thermo-economic performance of solar desalination via copper chips, nanofluid, and nano-based phase change material,” *Solar Energy*, vol. 224, pp. 1313–1325, Aug. 2021, doi: 10.1016/j.solener.2021.06.085.
- [185] S. Sun *et al.*, “3D-printed solar evaporator with seashell ornamentation-inspired structure for zero liquid discharge desalination,” *Water Res*, vol. 226, p. 119279, Nov. 2022, doi: 10.1016/j.watres.2022.119279.
- [186] S. Chaule, J. Hwang, S. Ha, J. Kang, J. Yoon, and J. Jang, “Rational Design of a High Performance and Robust Solar Evaporator via 3D-Printing Technology,” *Advanced Materials*, vol. 33, no. 38, Sep. 2021, doi: 10.1002/adma.202102649.
- [187] Y. Li *et al.*, “3D-Printed, All-in-One Evaporator for High-Efficiency Solar Steam Generation under 1 Sun Illumination,” *Advanced Materials*, vol. 29, no. 26, Jul. 2017, doi: 10.1002/adma.201700981.
- [188] Z. Wang *et al.*, “3D-Printed Bionic Solar Evaporator,” *Solar RRL*, vol. 6, no. 7, Jul. 2022, doi: 10.1002/solr.202101063.
- [189] K. Venkateshwaran, A. Kumar Kaviti, and V. V. D. Sahithi, “3D printed curved shape solar evaporator in producing distillate,” *Mater Today Proc*, Sep. 2023, doi: 10.1016/j.matpr.2023.08.360.
- [190] X. Wang, H. Zhou, Z. Chen, and X. Meng, “Synchrotron-based X-ray diffraction and absorption spectroscopy studies on layered LiNi_xMn_yCo_zO₂ cathode materials: A review,” *Energy Storage Mater*, vol. 49, pp. 181–208, Aug. 2022, doi: 10.1016/j.ensm.2022.04.012.
- [191] Y. Gong, X. Chen, and W. Wu, “Application of fourier transform infrared (FTIR) spectroscopy in sample preparation: Material characterization and mechanism investigation,” *Advances in Sample Preparation*, vol. 11, p. 100122, Aug. 2024, doi: 10.1016/j.sampre.2024.100122.
- [192] L. M. Alvarenga, T. P. Xavier, M. A. S. Barrozo, M. S. Bacelos, and T. S. Lira, “Dynamic analysis of reaction kinetics of carton packaging pyrolysis,” 2012, pp. 180–184. doi: 10.1016/B978-0-444-59507-2.50028-7.

- [193] P. Zambrano *et al.*, “Differential scanning calorimetry in drug-membrane interactions,” *Biochem Biophys Res Commun*, vol. 709, p. 149806, May 2024, doi: 10.1016/j.bbrc.2024.149806.
- [194] A. F. Ismail, K. C. Khulbe, and T. Matsuura, “RO Membrane Characterization,” in *Reverse Osmosis*, Elsevier, 2019, pp. 57–90. doi: 10.1016/B978-0-12-811468-1.00003-7.
- [195] K. Khalid, R. Ishak, and Z. Z. Chowdhury, “UV–Vis spectroscopy in non-destructive testing,” in *Non-Destructive Material Characterization Methods*, Elsevier, 2024, pp. 391–416. doi: 10.1016/B978-0-323-91150-4.00021-5.
- [196] T. G. Mayerhöfer, “Transition from the Bouguer-Beer-Lambert approximation to wave optics and dispersion theory,” in *Wave Optics in Infrared Spectroscopy*, Elsevier, 2024, pp. 11–45. doi: 10.1016/B978-0-443-22031-9.00010-0.
- [197] V. Abhilash, N. Rajender, and K. Suresh, “X-ray diffraction spectroscopy of polymer nanocomposites,” in *Spectroscopy of Polymer Nanocomposites*, Elsevier, 2016, pp. 410–451. doi: 10.1016/B978-0-323-40183-8.00014-8.
- [198] H. Belaid *et al.*, “Development of new biocompatible 3D printed graphene oxide-based scaffolds,” *Materials Science and Engineering: C*, vol. 110, p. 110595, May 2020, doi: 10.1016/j.msec.2019.110595.
- [199] S. R. Laraba *et al.*, “Enhancing Structural and Thermal Properties of Poly(lactic acid) Using Graphene Oxide Filler and Anionic Surfactant Treatment,” *Molecules*, vol. 28, no. 18, p. 6442, Sep. 2023, doi: 10.3390/molecules28186442.
- [200] T. Tábi, S. Hajba, and J. G. Kovács, “Effect of crystalline forms (α' and α) of poly(lactic acid) on its mechanical, thermo-mechanical, heat deflection temperature and creep properties,” *Eur Polym J*, vol. 82, pp. 232–243, Sep. 2016, doi: 10.1016/j.eurpolymj.2016.07.024.
- [201] V. S. G. Silverajah, N. A. Ibrahim, W. M. Z. W. Yunus, H. A. Hassan, and C. B. Woei, “A Comparative Study on the Mechanical, Thermal and Morphological Characterization of Poly(lactic acid)/Epoxidized Palm Oil Blend,” *Int J Mol Sci*, vol. 13, no. 5, pp. 5878–5898, May 2012, doi: 10.3390/ijms13055878.
- [202] S. Ambrus *et al.*, “Characterization and mechanical properties of fused deposited PLA material,” *Mater Today Proc*, vol. 45, pp. 4356–4363, 2021, doi: 10.1016/j.matpr.2021.02.760.

- [203] H. J. Yeh, "Ultrasonic welding of medical plastics," in *Joining and Assembly of Medical Materials and Devices*, Elsevier, 2013, pp. 296–323e. doi: 10.1533/9780857096425.3.296.
- [204] W. Zhou, Y. Cheng, K. Chen, G. Xie, T. Wang, and G. Zhang, "Thermal Conductivity of Amorphous Materials," *Adv Funct Mater*, vol. 30, no. 8, Feb. 2020, doi: 10.1002/adfm.201903829.
- [205] A. E. Kabeel, M. Abdelgaied, and A. Eisa, "Enhancing the performance of single basin solar still using high thermal conductivity sensible storage materials," *J Clean Prod*, vol. 183, pp. 20–25, May 2018, doi: 10.1016/j.jclepro.2018.02.144.
- [206] D. Vaes and P. Van Puyvelde, "Semi-crystalline feedstock for filament-based 3D printing of polymers," *Prog Polym Sci*, vol. 118, p. 101411, Jul. 2021, doi: 10.1016/j.progpolymsci.2021.101411.
- [207] I. Måge, U. Böcker, S. G. Wubshet, D. Lindberg, and N. K. Afseth, "Fourier-transform infrared (FTIR) fingerprinting for quality assessment of protein hydrolysates," *LWT*, vol. 152, p. 112339, Dec. 2021, doi: 10.1016/j.lwt.2021.112339.
- [208] M. Tanase-Opedal, E. Espinosa, A. Rodríguez, and G. Chinga-Carrasco, "Lignin: A Biopolymer from Forestry Biomass for Biocomposites and 3D Printing," *Materials*, vol. 12, no. 18, p. 3006, Sep. 2019, doi: 10.3390/ma12183006.
- [209] N. Choksi and H. Desai, "Synthesis of biodegradable polylactic acid polymer by using lactic acid monomer," *Int. J. Appl. Chem*, vol. 13, no. 2, pp. 377–384, 2017.
- [210] J. Muller, C. González-Martínez, and A. Chiralt, "Poly(lactic) acid (PLA) and starch bilayer films, containing cinnamaldehyde, obtained by compression moulding," *Eur Polym J*, vol. 95, pp. 56–70, Oct. 2017, doi: 10.1016/j.eurpolymj.2017.07.019.
- [211] S. Ebnesajjad, "Surface and Material Characterization Techniques," in *Surface Treatment of Materials for Adhesion Bonding*, Elsevier, 2006, pp. 43–75. doi: 10.1016/B978-081551523-4.50006-7.
- [212] A. Abdelbary, "Sliding mechanics of polymers," in *Wear of Polymers and Composites*, Elsevier, 2014, pp. 37–66. doi: 10.1533/9781782421788.37.

- [213] Q. Chen, J. D. Mangadlao, J. Wallat, A. De Leon, J. K. Pokorski, and R. C. Advincula, “3D Printing Biocompatible Polyurethane/Poly(lactic acid)/Graphene Oxide Nanocomposites: Anisotropic Properties,” *ACS Appl Mater Interfaces*, vol. 9, no. 4, pp. 4015–4023, Feb. 2017, doi: 10.1021/acsami.6b11793.
- [214] J. Drzeżdżon, D. Jacewicz, A. Sielicka, and L. Chmurzyński, “Characterization of polymers based on differential scanning calorimetry based techniques,” *TrAC Trends in Analytical Chemistry*, vol. 110, pp. 51–56, Jan. 2019, doi: 10.1016/j.trac.2018.10.037.
- [215] E. Ghanbari, S. J. Picken, and J. H. van Esch, “Analysis of differential scanning calorimetry (DSC): determining the transition temperatures, and enthalpy and heat capacity changes in multicomponent systems by analytical model fitting,” *J Therm Anal Calorim*, vol. 148, no. 22, pp. 12393–12409, Nov. 2023, doi: 10.1007/s10973-023-12356-1.
- [216] L. McKeen, “Introduction to the Physical, Mechanical, and Thermal Properties of Plastics and Elastomers,” in *The Effect of Sterilization on Plastics and Elastomers*, Elsevier, 2012, pp. 57–84. doi: 10.1016/B978-1-4557-2598-4.00003-4.
- [217] C. J. van Oss, “The Apolar and Polar Properties of Liquid Water and Other Condensed-Phase Materials,” in *Interface Science and Technology*, vol. 16, Department of Microbiology and Immunology, 2008, ch. 2, pp. 13–30. doi: 10.1016/S1573-4285(08)00202-0.
- [218] A. K. Thakur *et al.*, “Synergetic effect of absorber and condenser nano-coating on evaporation and thermal performance of solar distillation unit for clean water production,” *Solar Energy Materials and Solar Cells*, vol. 240, p. 111698, Jun. 2022, doi: 10.1016/j.solmat.2022.111698.
- [219] T. K. Murtadha, “Installing clear acrylic sheet to reduce unwanted sunlight waves that photovoltaic panels receive,” *Results in Engineering*, vol. 17, p. 100875, Mar. 2023, doi: 10.1016/j.rineng.2023.100875.
- [220] M. Ameri, H. Farzan, and M. Nobari, “Evaluation of Different Glazing Materials, Strategies, and Configurations in Flat Plate Collectors Using Glass and Acrylic Covers: An Experimental Assessment,” *Iranian Journal of Energy and Environment*, vol. 12, no. 4, pp. 297–306, 2021, doi: 10.5829/IJEE.2021.12.04.03.

- [221] Z. M. Omara, A. S. Abdullah, A. E. Kabeel, and F. A. Essa, "The cooling techniques of the solar stills' glass covers – A review," *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 176–193, Oct. 2017, doi: 10.1016/j.rser.2017.04.085.
- [222] R. K. Sambare, S. K. Dewangan, P. K. Gupta, and S. Joshi, "Energy, exergy and economic analyses of tubular solar still with various transparent cover materials," *Process Safety and Environmental Protection*, vol. 168, pp. 1101–1108, Dec. 2022, doi: 10.1016/j.psep.2022.10.064.
- [223] N. M. Shatar, M. F. M. Sabri, M. F. M. Salleh, and M. H. Ani, "Investigation on the performance of solar still with thermoelectric cooling system for various cover material," *Renew Energy*, vol. 202, pp. 844–854, Jan. 2023, doi: 10.1016/j.renene.2022.11.105.
- [224] R. Srivastava *et al.*, "Impact Strength of Various Types of Acrylic Resin: An In Vitro Study," *J Contemp Dent Pract*, vol. 24, no. 1, pp. 56–60, May 2023, doi: 10.5005/jp-journals-10024-3382.
- [225] M. Förch and F. Wellershoff, "Glass Strength for Impact and Blast Loading," *International Journal of Structural Glass and Advanced Materials Research*, vol. 5, no. 1, pp. 115–133, Jan. 2021, doi: 10.3844/sgamrsp.2021.115.133.
- [226] L. B. Manfredi, E. S. Rodríguez, M. Wladyka-Przybylak, and A. Vázquez, "Thermal degradation and fire resistance of unsaturated polyester, modified acrylic resins and their composites with natural fibres," *Polym Degrad Stab*, vol. 91, no. 2, pp. 255–261, Feb. 2006, doi: 10.1016/j.polymdegradstab.2005.05.003.
- [227] M. Kohl, *Performance and durability assessment: optical materials for solar thermal systems*. Elsevier, 2004.
- [228] J. S. Gawande and L. B. Bhuyar, "Effect of Shape of the Absorber Surface on the Performance of Stepped Type Solar Still," *Energy Power Eng*, vol. 05, no. 08, pp. 489–497, 2013, doi: 10.4236/epe.2013.58053.

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