OPEN ACCESS

AIM INTERNATIONAL LLC Publisher
Frontiers in Applied Engineering and Technology, 2024;1(01): 59-83
Website:https:/journal.aimintlllc.com/index.php/FAET

SUSTAINABLE WATER PURIFICATION TECHNIQUES: A REVIEW OF SOLAR-BASED DESALINATION METHODS

Md Rashedul Islam [1]
[1]Master of Civil & Environmental Engineering, Lamar University, Texas, USA
Email: rashedul.env@gmail.com

Abdullah-Al Abid [2]
[2]Master of Civil & Environmental Engineering, Lamar University, Texas, USA
Email: aabid@lamar.edu

Md Mazharul Islam [3]
[3]Graduate researcher, Civil Engineering, University of the District of Columbia, Washington, DC, USA
Email: mdmazharul.islam@udc.edu

MD Mahamudul Hasan [4]
[4]Graduate researcher, Industrial Engineering, Lamar University, Texas, USA
Email: mahamudul_hasan@hotmail.com

Keywords

Solar Desalination
Sustainable Water Purification
Renewable Energy
Solar Stills
Multi-Effect Distillation

ABSTRACT

Global water scarcity continues to pose a critical challenge, driving the need for sustainable water purification solutions. Solar desalination has emerged as a promising approach due to its reliance on renewable solar energy and minimal environmental impact. This study systematically reviews and synthesizes findings from a comprehensive set of 100 peer-reviewed articles to evaluate advancements in solar desalination technologies, including solar stills, photovoltaic-powered reverse osmosis (PV-RO) systems, hybrid solar desalination, and the application of nanotechnology. The review highlights significant progress in improving the efficiency, scalability, and cost-effectiveness of these systems, particularly through innovations such as multi-stage designs, advanced membrane materials, energy recovery devices, and the integration of phase change materials (PCMs) for thermal storage. Additionally, the incorporation of nanomaterials has proven effective in enhancing thermal conductivity and reducing fouling, thereby optimizing water output and system longevity. Findings also reveal the substantial environmental benefits of solar desalination, which can reduce the carbon footprint of water production by up to 70%, aligning with the United Nations Sustainable Development Goals (SDGs) related to clean water access and climate action. However, challenges remain, particularly concerning the initial capital costs and the need for further technological advancements to achieve widespread adoption. This review underscores the critical role of continued research, innovation, and supportive policies in scaling solar desalination technologies as a sustainable solution to global water scarcity.

1 INTRODUCTION

Water scarcity is an escalating global issue, exacerbated by rapid population growth, industrialization, and climate change (Ge et al., 2005). According to the United Nations (2022), approximately 2.3 billion people live in water-stressed regions, with predictions indicating that by 2050, nearly half of the global population may face severe water shortages. Conventional water sources, such as groundwater and freshwater reserves, are increasingly becoming insufficient to meet the rising demand (Boffa et al., 2019). In this context, desalination, the process of removing salts and impurities from seawater or brackish water, has emerged as a vital technology to augment water supplies, especially in arid and coastal regions.

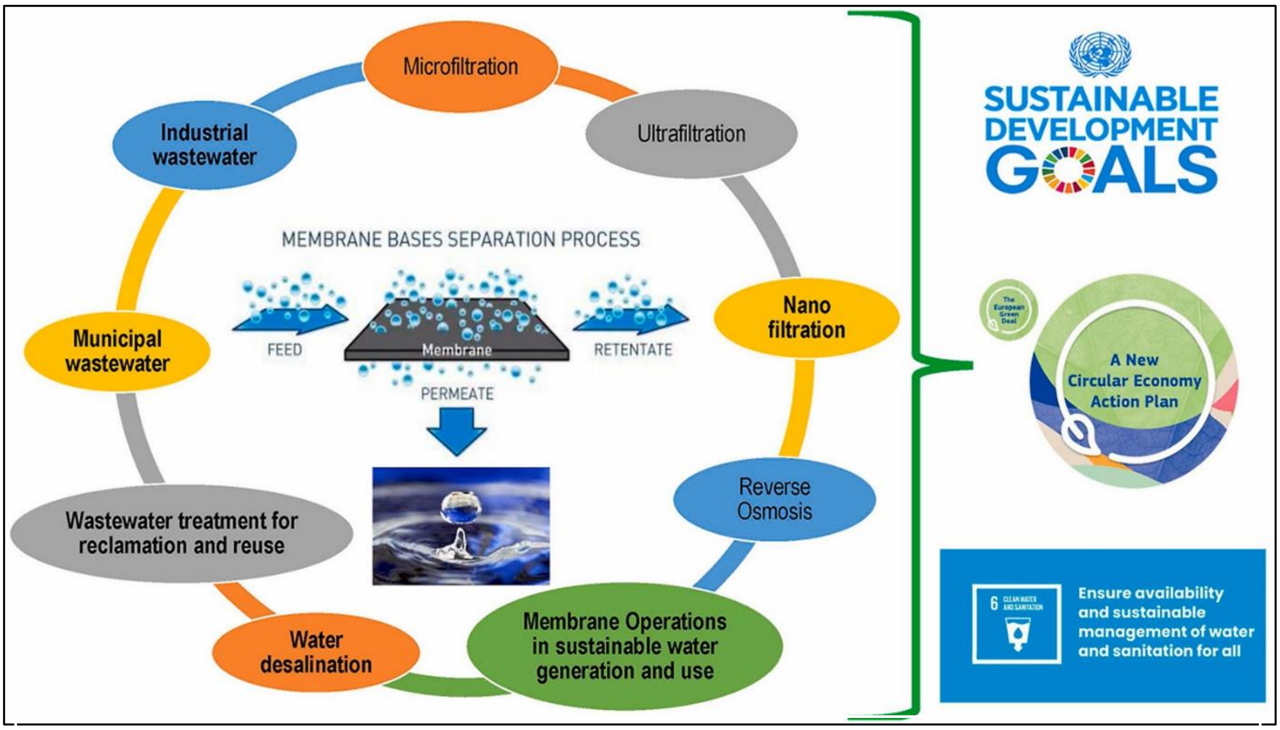
Received: 10th October, 2024 **Accepted**: 30th November,2024 **Published**: 03rd December,2024

However, traditional desalination techniques, such as reverse osmosis and thermal distillation, are energy-intensive and often rely on non-renewable fossil fuels, which contribute to greenhouse gas emissions and environmental degradation (Singh & Singh, 2016). As a sustainable alternative, solar-based desalination systems offer a promising solution by leveraging renewable solar energy for water purification (Lee et al., 2022).

Solar desalination utilizes the abundant solar radiation available in many regions, converting it into thermal or electrical energy to drive desalination processes (McGuigan et al., 2012). Various solar desalination techniques, including solar stills, solar-powered reverse osmosis, and solar-assisted multi-effect distillation, have been developed and optimized over the past decade (Chu et al., 2019). These methods not only reduce dependency on fossil fuels but also minimize the operational costs associated with traditional desalination systems (McGuigan et al., 1999). Recent advancements in material science and thermal energy storage have further improved the efficiency of solar desalination technologies, making them more viable for large-scale implementation (Rainey & Harding, 2005). By utilizing solar energy, these systems can operate independently in remote and off-grid locations, making them particularly suitable for regions with limited access to conventional energy sources (Müller et al., 2017). Despite the potential benefits, solar desalination faces several challenges that hinder its widespread adoption. Key issues include the intermittency of solar radiation, which affects the continuous operation of desalination systems, and the relatively high initial capital costs compared to conventional methods (Ericsson et al., 2001). Moreover, achieving efficient thermal management in solar stills and hybrid systems remains a significant technical hurdle (Ishaku et al., 2011). However, recent research indicates that integrating solar desalination with energy storage systems and hybridizing it with other renewable energy sources can enhance its performance and reliability (Tang et al., 2018). For instance, hybrid solar desalination systems that combine photovoltaic panels with thermal collectors have shown promising results in increasing water output while reducing energy consumption (Yuan et al., 2021).

Research in the field of solar desalination is increasingly focused on optimizing system design, improving thermal efficiency, and developing advanced materials to reduce heat loss (Karami et al., 2020). Innovative approaches, such as the use of nanomaterials, phase change materials, and multi-stage

Figure 1:Innovative Membrane-Based Separation Processes for Sustainable Water Management



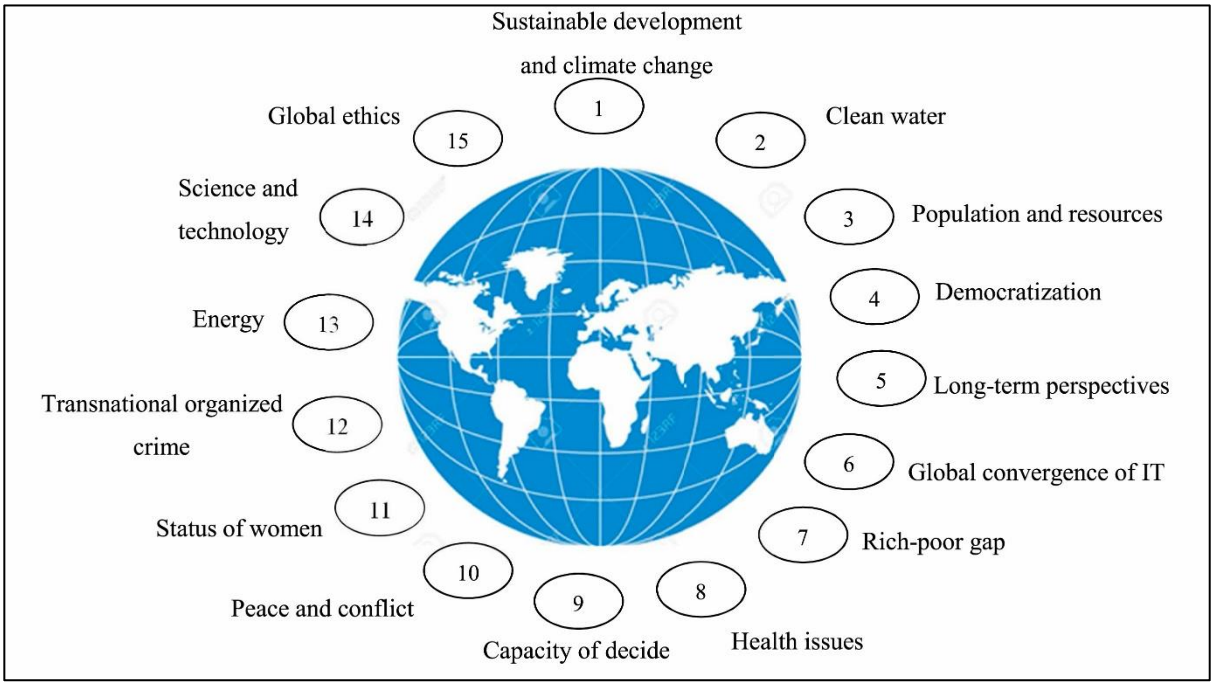
Source: Issaoui et al (2022).

evaporation techniques, have demonstrated significant improvements in desalination efficiency (Aboulella et al., 2022). Additionally, the integration of artificial intelligence and machine learning algorithms for real-time monitoring and control of desalination processes is gaining traction as a means to optimize system performance and reduce maintenance costs (Song et al., 2016). By leveraging these technological advancements, solar desalination could play a pivotal role in addressing global water shortages while contributing to sustainable development goals. The importance of solar desalination extends beyond providing potable water; it also aligns with the global transition towards cleaner energy and sustainable resource management (Zhang et al., 2008). Countries with high solar irradiance, such as those in the Middle East, North Africa, and South Asia, are particularly well-positioned to benefit from solar-based desalination systems (Bao et al., 2018). Studies have shown that solar desalination can be a cost-effective solution for rural and island communities where centralized water treatment facilities are either unavailable or impractical (Karami et al., 2020). As water scarcity continues to intensify, there is a pressing need to advance research and policy frameworks that support the adoption of solar desalination technologies (Biscardi & Duranceau, 2016). The primary objective of this review is to critically analyze the current state of solar-based desalination techniques, with a focus on identifying advancements, challenges, and opportunities for future development. This review aims to provide a comprehensive understanding of how solar-powered desalination systems can be optimized to address the pressing issue of water scarcity in a sustainable manner. By synthesizing findings from recent studies, the paper seeks to evaluate various solar desalination methods—such as solar stills, solar-assisted multi-effect distillation, and solar-powered reverse osmosis—and their potential applications in both urban and rural contexts. Additionally, the review intends to highlight key technological innovations that have enhanced the efficiency and cost-effectiveness of these systems while also identifying existing barriers to their large-scale deployment. Ultimately, this review endeavors to contribute to the ongoing discourse on sustainable water management by offering insights into how solar desalination can be integrated into global water supply strategies, particularly in regions facing acute water shortages.

2 LITERATURE REVIEW

Solar-based desalination has emerged as a critical area of research in response to the increasing demand for

Figure 2:Addressing Global Challenges Through Sustainable Development



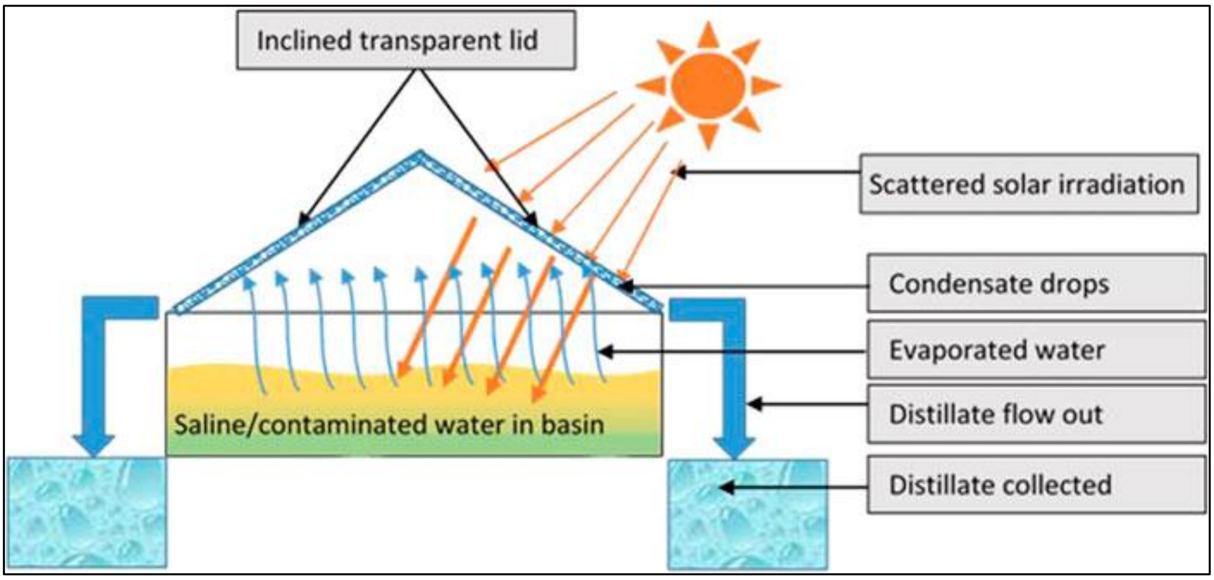
Source: Issaoui et al (2022).

sustainable water purification solutions. As conventional desalination technologies are heavily reliant on fossil fuels, which are both costly and environmentally detrimental, the transition to solar-powered systems is seen as a promising alternative (Montgomery & Elimelech, 2007). This section delves into the existing literature to explore various solar desalination techniques, their efficiencies, technological advancements, and the associated challenges. The review synthesizes recent findings from both theoretical and empirical studies to provide a holistic understanding of the potential and limitations of solar desalination technologies. By examining factors such as system design, energy conversion efficiency, material innovations, and economic viability, this literature review aims to present a thorough evaluation of the current state of solar desalination research. The insights gathered from this analysis will serve as a foundation for identifying areas where further research and technological development are required.

2.1 *Solar Desalination Technologies*

Photovoltaic-driven desalination systems, particularly those that utilize solar-powered reverse osmosis (PV-RO), have gained traction as an effective method to desalinate seawater, especially in regions with abundant sunlight (Manikandan et al., 2021). Unlike solar stills, PV-RO systems convert solar energy directly into electricity, which is used to power high-pressure pumps to drive the desalination process (Ahmad et al., 2020). Recent advancements in membrane technology, such as the development of energy-efficient and durable membranes, have significantly increased the efficiency of PV-RO systems (Lin & Valsaraj, 2005). Moreover, hybrid systems that combine solar thermal energy with photovoltaic power have demonstrated increased desalination rates and reduced energy consumption (Huh et al., 2020). These hybrid approaches leverage the strengths of both thermal and photovoltaic technologies, making them particularly effective in maximizing water output in diverse environmental conditions (Fan et al., 2017). Several landmark projects have paved the way for the current advancements in solar desalination. For instance, large-scale implementations in the Middle East and North Africa have demonstrated the potential of solar-powered desalination to supply potable water to arid regions (Ahmad et al., 2020). Research initiatives, such as those conducted in Saudi Arabia, have focused on integrating solar desalination with thermal energy storage to extend operation during periods of low solar irradiance (Sharma & Bhattacharya, 2016). Additionally, studies in Australia and India have explored decentralized solar desalination systems to provide clean water in off-grid rural areas (Zhang et al., 2015). These projects highlight the feasibility of solar desalination as a sustainable solution for water scarcity and demonstrate the importance of continued research and innovation in this field. As a result, solar desalination remains a critical

Figure 3: Solar Still Design for Efficient Water Desalination



Source: Choong et al. (2020).

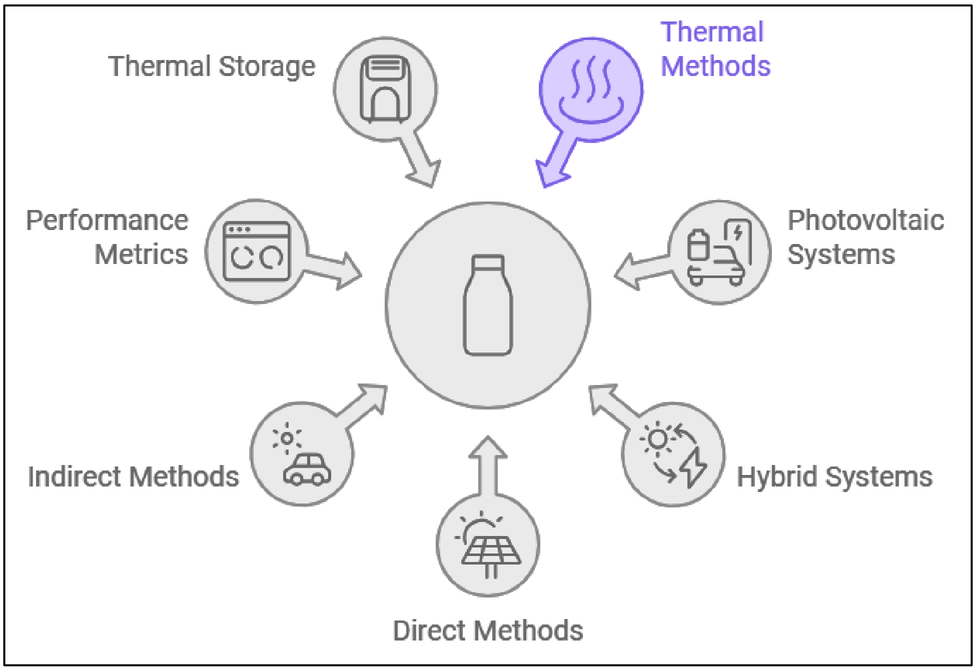
focus area for achieving sustainable water management in the context of increasing global water stress (Scaratti et al., 2020).

2.2 *Fundamentals of Solar Energy Utilization in Desalination*

The application of solar energy in desalination leverages the natural conversion of solar radiation into usable forms of energy to drive water purification processes. Fundamentally, solar desalination systems are classified into three primary categories: thermal, photovoltaic, and hybrid methods (Rainey & Harding, 2005). Thermal methods utilize solar heat to evaporate water, which is then condensed into purified water, as seen in technologies like solar stills and multi-effect distillation (Samaei et al., 2018;Shamim, 2022). In contrast, photovoltaic systems directly convert solar energy into electricity using solar panels, which then powers desalination units, such as reverse osmosis systems (Shang et al., 2017). Recent research has focused on hybrid systems that combine both thermal and photovoltaic components to optimize energy usage, improve efficiency, and enhance the overall desalination rate (Asif & Zhang, 2021). These hybrid systems are particularly advantageous in regions with fluctuating solar irradiance, where combining energy sources can ensure continuous operation (Zhang et al., 2021). Moreover, direct and indirect solar desalination systems differ in how they utilize solar energy for water purification. Direct solar desalination involves capturing sunlight directly on the water source, using solar stills or concentrated solar collectors to heat water and induce evaporation (Garmsiri et al., 2017). This method, while simple, is often constrained by lower efficiency due to heat losses and limited surface area for solar absorption (Song et al., 2022). Conversely, indirect solar desalination systems, such as photovoltaic-powered reverse osmosis (PV-RO), employ solar panels to generate electricity, which is then used to power desalination processes (Manikandan et al., 2021). Indirect systems tend to be more efficient, particularly in large-scale applications, due to their ability to store electrical energy and operate independently of solar radiation availability (Ahmad et al., 2020). Studies have shown that indirect methods can achieve higher water output rates, making them more suitable for industrial-scale desalination (Ahmad et al., 2020; Nielsen et al., 2022).

The efficiency of solar desalination systems is typically measured using various performance indicators, such as water production rate, specific energy consumption, and thermal efficiency (Zhang et al., 2019). For thermal desalination systems, the key metric is the gain output ratio (GOR), which indicates the amount of fresh water produced per unit of energy consumed (Nielsen et al., 2022). In photovoltaic-based systems, metrics like energy conversion efficiency and system performance ratio are used to evaluate the effectiveness of solar panels in generating sufficient power for desalination

Figure 4: Enhancing Solar Desalination Efficiency



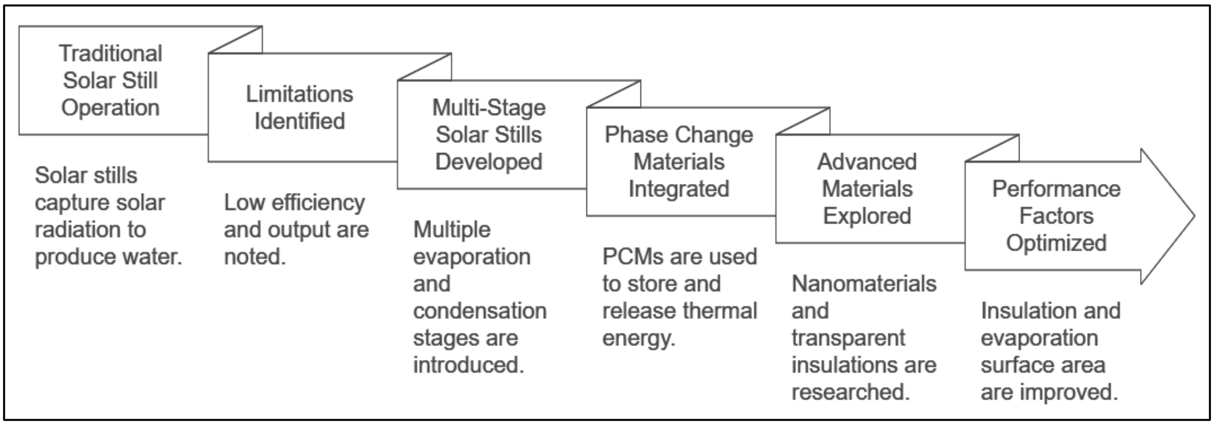
processes (Ahmad et al., 2020). Additionally, the integration of thermal storage materials, such as phase change materials (PCMs), has been shown to enhance the efficiency of solar desalination by extending operational hours beyond peak sunlight periods (Lin & Valsaraj, 2005). These advancements are critical for optimizing desalination efficiency, particularly in off-grid and remote locations where energy resources are limited (Ge et al., 2005). Despite these advancements, achieving high efficiency in solar desalination systems remains a significant challenge due to the variability in solar energy availability (Sun et al., 2021). For instance, hybrid systems have been developed to overcome the limitations of single-method approaches by combining thermal collectors with photovoltaic panels to maximize energy utilization (Gao & Xu, 2019). Such systems have demonstrated improved performance in diverse climatic conditions, where both direct and diffuse solar radiation can be effectively harnessed (Stauber et al., 2006). Further, integrating artificial intelligence and predictive algorithms for optimizing the operation of solar desalination systems is gaining attention in recent research, as it offers a pathway to increase system reliability and reduce energy consumption (Nielsen et al., 2022). These innovations are pivotal in enhancing the scalability and economic feasibility of solar desalination technologies.

2.3 *Solar Still Technologies: Design, Efficiency, and Improvements*

Solar stills, one of the earliest forms of solar desalination technologies, have been widely studied for their simplicity and cost-effectiveness in producing potable water (Nielsen et al., 2022). Traditional solar stills operate by capturing solar radiation to heat water, causing it to evaporate and then condense on a cooler surface, where it is collected as purified water (Athanasekou et al., 2015). While the fundamental design of solar stills has remained largely unchanged, their low water output and efficiency have been significant limitations (Gao & Xu, 2019). Research has shown that the efficiency of traditional solar stills is largely constrained by heat losses and the limited surface area available for evaporation (Cai et al., 2020). Despite these challenges, solar stills are still widely used in remote and off-grid regions where other forms of desalination are not economically feasible (Lin & Valsaraj, 2005). To enhance the efficiency of solar stills, recent innovations have focused on improving their design and incorporating advanced materials. One of the most effective modifications is the development of multi-stage solar stills, which increase the water production rate by using multiple evaporation and condensation stages within a single system (Fehri et al., 2019). Studies have demonstrated that multi-stage stills can significantly enhance water yield compared to single-stage designs by reusing latent heat (Sharma & Bhattacharya, 2016). Additionally, the integration of phase change materials (PCMs) into solar stills has gained attention for its ability to store thermal energy and release it during non-sunlight hours, thereby extending operational efficiency beyond daylight periods (Tai et al., 2020). These advancements not only improve water output but also reduce the dependency on continuous solar irradiance, making the systems more reliable in varying climatic conditions (Huh et al., 2020).

Material selection plays a crucial role in the efficiency of solar stills, with recent research exploring the use of advanced materials to improve thermal insulation and

Figure 5: Enahancements in Solar Still Technologies



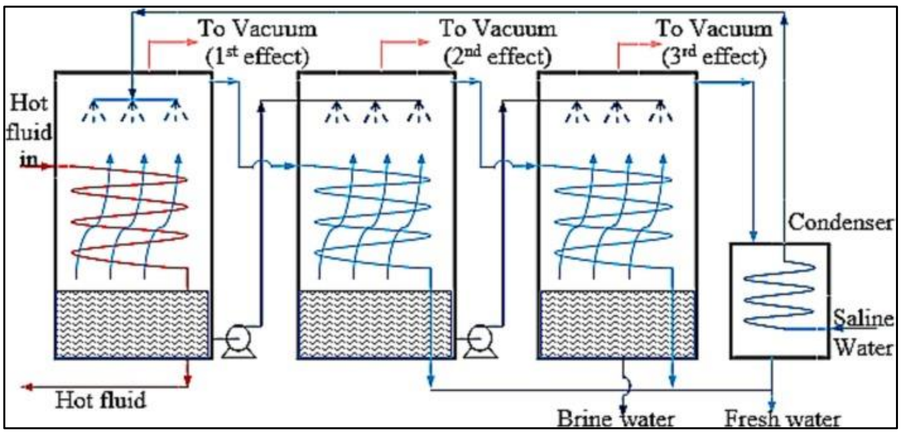
reduce heat losses (Fan et al., 2017). For instance, nanomaterial coatings on the interior surfaces of stills have been shown to enhance solar absorption and reduce thermal radiation losses (Kim et al., 2008). Moreover, the use of transparent insulation materials, such as double-glazed glass covers, helps to trap more solar energy, increasing the evaporation rate (Zhang et al., 2019). Studies have also investigated the impact of basin materials on water productivity, finding that black-painted basins or absorptive materials can significantly boost the evaporation process (Suresh & Pugazhenthi, 2017). These design optimizations have contributed to making solar stills more efficient and viable for large-scale desalination projects.Moreover, several factors influence the overall performance of solar stills, including insulation quality, evaporation surface area, and water depth in the basin (Tai et al., 2020). For example, reducing the water depth has been found to increase the surface area for evaporation, thereby enhancing productivity (Fan et al., 2017). Insulation improvements, such as the use of reflective coatings and thermal barriers, have also been shown to reduce heat losses and maintain higher temperatures within the still, which is critical for efficient water vapor generation (Kim et al., 2008). Additionally, optimizing the angle of the glass cover to maximize solar incidence can further improve water output, especially in regions with high solar irradiance (Xing et al., 2020). As a result of these enhancements, solar still technology is gradually becoming more efficient, making it a viable option for sustainable water production in resource-constrained environments.

2.4 *Solar-Assisted Multi-Effect Distillation (MED) Systems*

Multi-effect distillation (MED) systems are widely recognized for their efficiency in desalinating seawater by utilizing multiple stages of evaporation and condensation to maximize water production (Fan et al., 2017). The basic working principle involves heating saline water to generate steam, which is then condensed to produce fresh water in successive stages, utilizing the latent heat from previous stages to increase overall efficiency (Xing et al., 2020). This cascading effect reduces the amount of thermal energy required, making MED systems more energy-efficient compared to single-stage distillation methods (Manikandan et al., 2021). Traditionally, MED systems have relied on fossil fuels, but with the increasing focus on sustainability, solar energy has been integrated into these systems to reduce their environmental impact (Zhang et al., 2015). This integration has enabled the use of solar thermal energy as a heat source, making MED systems a viable solution for water desalination in regions with abundant sunlight (Ge et al., 2005).

Recent advancements have focused on integrating solar thermal collectors with MED systems to enhance energy efficiency and reduce operational costs (Alkhalidi et al., 2021). By using solar thermal collectors, the systems can harness solar radiation to generate the necessary heat for the distillation process, significantly reducing reliance on non-renewable energy sources (Cai et al., 2020; Chen et al., 2016). Studies have demonstrated that flat-plate and parabolic trough solar collectors are particularly effective in supplying the consistent heat required for MED operations (Sharma & Bhattacharya, 2016).

Figure 6:Multi-effect distillation (MED)



Additionally, innovative designs that incorporate thermal energy storage systems, such as phase change materials (PCMs), allow for continuous operation during periods of low solar irradiance (Ge et al., 2005). This has proven essential for increasing the reliability of solar-assisted MED systems in regions with variable weather conditions, thereby extending their applicability beyond areas with high solar insolation (Jamalludin et al., 2020).

The integration of solar thermal energy with MED systems has also contributed to improvements in scalability and cost-effectiveness. Research indicates that large-scale solar-assisted MED systems can be deployed to meet the water demands of both industrial and municipal applications (Huihui et al., 2020). For instance, the combination of solar power with multi-effect distillation not only reduces the overall energy consumption but also enhances the scalability of these systems, making them suitable for deployment in water-scarce regions (Cai et al., 2020). The scalability of MED systems is further supported by advancements in heat exchanger designs, which improve heat transfer efficiency and reduce thermal losses (Sundar, 2023). These developments have positioned solar-assisted MED as a competitive alternative to conventional desalination technologies, particularly in coastal regions with high water demand and limited access to fresh water sources (Singh & Singh, 2016). Despite the promising potential of solar-assisted MED systems, challenges remain in terms of optimizing energy efficiency and reducing costs (Jamalludin et al., 2020). One of the primary issues is the high initial capital investment required for solar thermal collectors and thermal storage units (Huihui et al., 2020). However, ongoing research is focused on developing more cost-effective materials and innovative designs to improve the economic feasibility of these systems (Sundar, 2023). For example, recent studies have explored the use of nanofluids and advanced coatings to enhance the thermal conductivity of solar collectors, thereby increasing the efficiency of heat absorption (Sharma & Bhattacharya, 2016). Additionally, hybrid systems that combine MED with other renewable energy sources, such as wind or geothermal energy, are being investigated to further optimize performance and reduce costs (Laxman et al., 2015). These advancements are crucial for expanding the adoption of solar-assisted MED systems in water-scarce regions, contributing to sustainable water resource management.

2.5 *Photovoltaic-Powered Reverse Osmosis: Opportunities and Challenges*

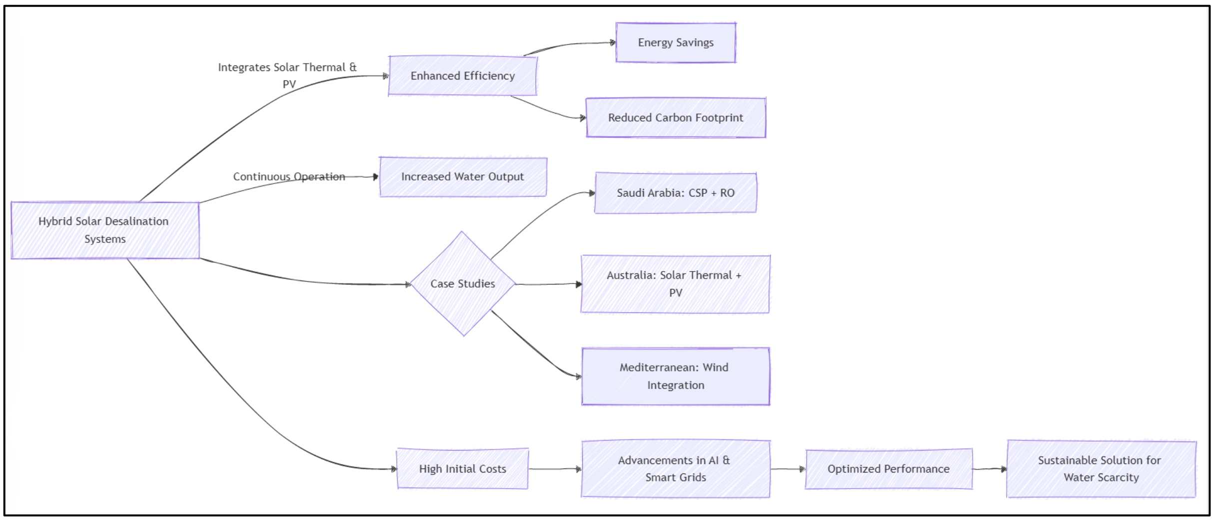
Photovoltaic-powered reverse osmosis (PV-RO) systems have emerged as a promising solution for desalination, especially in regions with high solar irradiance and limited access to traditional energy sources (Montazeri & Kolliopoulos, 2022). These systems leverage solar panels to generate electricity, which powers high-pressure pumps to force saline water through semi-permeable membranes, removing salts and impurities to produce fresh water (Xu et al., 2020). Unlike thermal desalination processes, PV-RO systems are highly efficient in terms of energy consumption and do not rely on thermal energy, making them ideal for decentralized and off-grid applications (Sajid & Bicer, 2022). The adoption of PV-RO has grown due to its scalability and adaptability, enabling small to large-scale installations depending on the specific water needs of the community (Zhang et al., 2013). These systems have been successfully deployed in remote areas where the availability of fresh water is scarce, demonstrating their potential to improve water accessibility in developing regions (Hu et al., 2015).

Advancements in membrane technology and energy recovery devices have played a critical role in enhancing the efficiency of PV-RO systems. Recent developments in thin-film composite membranes have significantly improved the salt rejection rates and reduced the energy required for desalination (Sharma & Bhattacharya, 2016). Additionally, the use of advanced energy recovery devices, such as pressure exchangers, has led to a reduction in the energy footprint of PV-RO systems by up to 60% (Gao et al., 2022). These devices work by recycling the pressure from the brine stream to reduce the overall energy needed to drive the process, making the systems more energy-efficient (Alkhalidi et al., 2021). The integration of nanomaterials in membrane manufacturing has further enhanced the permeability and fouling resistance of RO membranes, thereby increasing the longevity and reducing maintenance costs of PV-RO systems (Sundar, 2023). Such technological improvements are essential for optimizing the performance of PV-RO systems, especially in regions where consistent maintenance is challenging (Gao et al., 2022). Moreover, economic feasibility remains a critical factor influencing the widespread adoption of PV-RO systems, particularly in low-income and remote communities (Chen et al., 2016). While the initial capital investment for installing photovoltaic panels and RO units is relatively high, the long-term operational costs are significantly lower compared to traditional desalination systems that rely on fossil fuels (Pauzan et al., 2021). Studies have shown that the levelized cost of water (LCOW) for PV-RO systems can be competitive in regions with high solar insolation, making them an attractive option for sustainable water supply (Lee et al., 2022). For instance, projects in North Africa and the Middle East have demonstrated the economic viability of PV-RO in providing affordable drinking water to rural populations (Sundar, 2023). Additionally, the decreasing cost of solar photovoltaic panels over the past decade has further improved the economic outlook for PV-RO systems, enabling broader adoption (Pauzan et al., 2021). Numerous case studies highlight the successful implementation of PV-RO systems in off-grid and remote areas, showcasing their potential to address water scarcity sustainably (Huihui et al., 2020). For example, a project in the Maldives utilized PV-RO to supply fresh water to island communities, significantly reducing their dependence on diesel-powered desalination (Gu et al., 2019). Similarly, in sub-Saharan Africa, PV-RO systems have been deployed to provide potable water in rural villages, where access to freshwater sources is limited (Chang et al., 2019). These systems not only improve water security but also contribute to reducing the carbon footprint associated with conventional desalination processes (Lu et al., 2016). As the technology continues to advance, the integration of artificial intelligence for real-time monitoring and optimization of PV-RO systems is being explored to further enhance their efficiency and reliability in diverse operating conditions (Doménech et al., 2022).

2.6 *Hybrid Solar Desalination Systems: Combining Technologies for Enhanced Performance*

Hybrid solar desalination systems have emerged as a strategic approach to overcoming the limitations of conventional desalination technologies by integrating multiple renewable energy (Smieja, 2011). These systems typically combine solar thermal and photovoltaic (PV) technologies to enhance energy efficiency and maximize water production (Montazeri & Kolliopoulos, 2022). The integration of different energy sources allows hybrid systems to harness the benefits of both solar heat and electricity, optimizing the desalination process by enabling continuous operation even in varying climatic conditions (Pauzan et al., 2021). For instance, solar thermal energy can be used for heating and evaporation, while photovoltaic power drives auxiliary systems, such as pumps, in reverse osmosis (RO) setups (Gu et al., 2019). By utilizing a hybrid approach, these systems can adapt to diverse environmental conditions, making them particularly effective in remote or off-grid locations where water scarcity is prevalent (Montazeri & Kolliopoulos, 2022). The benefits of hybrid solar desalination systems extend beyond increased water output; they also significantly reduce energy consumption and improve overall system efficiency (Lee et al., 2022). One of the main advantages is that these systems can store excess

Figure 7: Hybrid Solar Desalination Systems



thermal energy using phase change materials (PCMs) or other storage technologies, enabling continuous desalination during periods of low solar irradiance (Gu et al., 2019). Hybrid systems are also capable of utilizing waste heat from other processes, further enhancing energy efficiency and reducing the overall operational cost (Smieja, 2011). This integration not only ensures a more stable freshwater output but also contributes to reducing the carbon footprint associated with traditional desalination technologies that depend on fossil fuels (Lu et al., 2016). The optimization of water output and energy use has made hybrid systems a promising solution for sustainable desalination, particularly in areas where conventional energy sources are limited or costly (Pauzan et al., 2021).

Numerous case studies demonstrate the success of hybrid solar desalination systems in real-world applications, showcasing their potential to meet the growing demand for potable water in arid regions (Lee et al., 2022; Pauzan et al., 2021). For example, a project in Saudi Arabia combined concentrated solar power (CSP) with reverse osmosis, achieving a significant reduction in energy consumption while maintaining high water output (Salhi et al., 2022). Another notable application in Australia utilized a hybrid system that integrated solar thermal collectors with PV modules to desalinate seawater, resulting in increased efficiency and reduced environmental impact (Smieja, 2011). These projects highlight the versatility of hybrid systems in adapting to local conditions, ensuring water security while leveraging renewable energy sources (Song et al., 2016). Additionally, studies in the Mediterranean region have explored the use of wind energy as a supplementary source in hybrid desalination, further demonstrating the flexibility of these systems in harnessing multiple renewable resources (Xu et al., 2020). Despite their advantages, hybrid solar desalination systems still face challenges in terms of initial capital costs and system complexity (Smieja, 2011). However, advancements in material science and system design are making these technologies more cost-effective and accessible for broader adoption (Song et al., 2016). Innovations in smart grid integration and artificial intelligence are being explored to optimize the operation of hybrid systems, ensuring efficient energy use and reducing maintenance requirements (Lu et al., 2016). The successful deployment of hybrid solar desalination in various regions has demonstrated its potential to provide a sustainable and resilient solution to water scarcity, particularly in areas with limited access to conventional energy sources (Song et al., 2016). As technology continues to advance, hybrid systems are poised to play a crucial role in the future of sustainable desalination.

2.7 *Materials and Nanotechnology in Solar Desalination*

Nanomaterials have become a focal point in advancing solar desalination technologies due to their ability to enhance thermal conductivity and minimize heat losses (Chen et al., 2022; Sultana & Aktar, 2024; Uddin, 2024; Uddin & Hossan, 2024). These materials, with their high surface area-to-volume ratios, can significantly improve heat transfer rates, thereby boosting the efficiency of solar desalination systems (Shanmugan et al., 2018). For instance, incorporating nanoparticles like graphene and carbon nanotubes into solar collectors has been shown to increase solar absorption and thermal conductivity (Chen et al., 2022). Studies have demonstrated that the addition of nanofluids to water can enhance the evaporation rate, thereby increasing the water output in solar stills and multi-effect distillation (MED) systems (Sharshir et al., 2017; Shorna et al., 2024; Shorna et al., 2024; Sohel et al., 2024). By optimizing the heat transfer properties, nanomaterials reduce energy losses and enhance the overall performance of solar desalination units, especially in fluctuating environmental conditions (Al-Harahsheh et al., 2022).

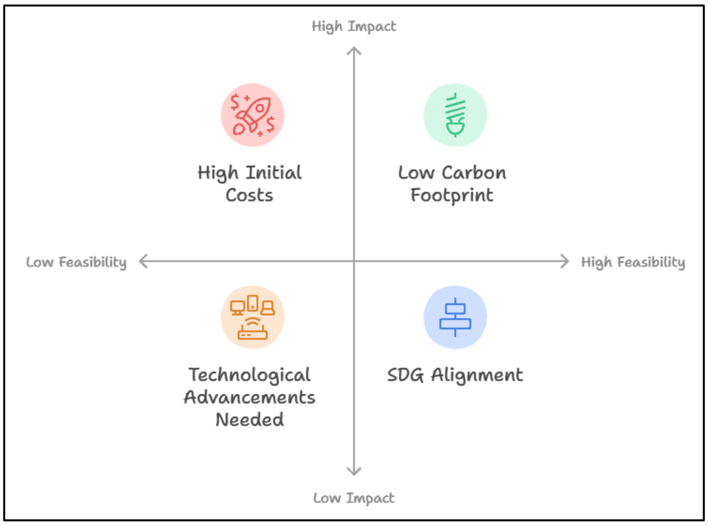
In addition to nanomaterials, advanced coatings and phase change materials (PCMs) play a crucial role in enhancing the efficiency of solar desalination systems (Alawee et al., 2022). Coatings with high absorptivity and low emissivity, such as black oxide or selective solar absorbers, are used to maximize the capture of solar radiation while minimizing heat losses through radiation (Rahman, 2024; Rahman et al., 2024; Rahman et al., 2024; Shamsuzzaman et al., 2024; Zeidman et al., 2020). PCMs, on the other hand, are integrated into desalination systems to store excess thermal energy during peak sunlight hours and release it when solar intensity is low (Alqsair et al., 2022). This thermal storage capability ensures that desalination processes can continue during cloudy periods or at night, thus improving water production rates (Kandeal et al., 2021). Research has shown that the combination of advanced coatings and PCMs can significantly reduce the energy consumption of solar stills and enhance their reliability in diverse climatic conditions (Rahman, 2024; Shatar et al., 2023). Morteover, solar absorbers designed with nanomaterials are another innovative approach to improving the efficiency of solar desalination (Shanmugan et al., 2018). These absorbers are often engineered to have high absorption coefficients while maintaining low thermal conductivity, allowing them to efficiently convert solar energy into heat (Lim et al., 2018). The use of nanostructured coatings, such as titanium dioxide and silica-based layers, enhances the light absorption capabilities of solar panels, reducing reflection losses (Sharshir et al., 2017). Additionally, porous materials like aerogels have been explored for their insulating properties, which help retain heat within desalination systems (Kandeal et al., 2021; Mosleuzzaman et al., 2024; Mosleuzzaman et al., 2024; Nandi et al., 2024). The integration of these materials into hybrid solar desalination units not only improves water output but also extends the operational lifespan of the systems by reducing wear and tear due to high temperatures (Ray et al., 2020). Moreover, emerging trends in material science are continuously pushing the boundaries of what is possible in solar desalination applications (Chen et al., 2022; Mazumder et al., 2024; Alam, 2024; Mosleuzzaman et al., 2024). Innovations such as photothermal nanomaterials, which convert light into heat with high efficiency, are being explored to further enhance the performance of solar stills and reverse osmosis systems (Ray et al., 2020). Moreover, self-cleaning coatings that utilize nanotechnology to prevent fouling and scaling on solar collectors are being developed to reduce maintenance needs (Alam et al., 2024; Hasan et al., 2024; Islam et al., 2024; Zeidman et al., 2020). Researchers are also investigating the use of bio-inspired materials, such as hydrogels and superhydrophobic surfaces, to improve water collection efficiency in solar desalination (Alqsair et al., 2022). These advancements highlight the potential of materials science to revolutionize solar desalination, making it a more sustainable and cost-effective solution for addressing global water scarcity (Sathish et al., 2022).

2.8 *Sustainable Development and Environmental Impact of Solar Desalination*

Solar desalination presents a significant opportunity for sustainable water management, particularly in regions facing acute water scarcity and environmental challenges (Singh & Singh, 2016). By harnessing renewable solar energy, these systems reduce dependence on fossil fuel-powered desalination technologies, which are known to produce greenhouse gases and exacerbate climate change (Shanmugan et al., 2018). The environmental benefits of solar desalination include a lower carbon footprint, as it primarily relies on clean energy sources with minimal emissions (Ray et al., 2020). Unlike conventional methods, solar-powered systems do not release harmful by-products or consume large quantities of non-renewable energy resources, thus aligning with global efforts to mitigate the effects of climate change (Zeidman et al., 2020). These benefits are crucial in addressing both water scarcity and environmental degradation, particularly in developing countries where access to sustainable water solutions is limited (Ray et al., 2020).

Transitioning to solar desalination can also play a vital role in reducing the carbon footprint associated with freshwater production (Alqsair et al., 2022). Traditional desalination methods, such as reverse osmosis and multi-effect distillation, are energy-intensive and often powered by fossil fuels, contributing to high levels of carbon dioxide emissions (Singh & Singh, 2016). Solar desalination systems, on the other hand, leverage abundant solar radiation to produce freshwater, reducing the need for energy derived from carbon-intensive sources (Shatar et al., 2023). Studies have shown that integrating solar energy into desalination can cut emissions by up to 70% compared to conventional systems (Shanmugan et al., 2018). Additionally, innovations like hybrid systems that combine solar power with other renewable sources,

Figure 8: Solar Desalination Benefirs and Challenges



such as wind energy, can further optimize energy use and minimize environmental impact (Zeidman et al., 2020).

The potential of solar desalination extends beyond environmental benefits, as it also supports several of the United Nations Sustainable Development Goals (SDGs) (Ray et al., 2020). Specifically, solar desalination aligns with SDG 6, which focuses on ensuring access to clean water and sanitation for all (United Nations, 2022). By providing a sustainable and decentralized solution for water purification, solar desalination can improve water access in remote and underserved communities, thus contributing to poverty alleviation (Lim et al., 2018). Moreover, solar desalination supports SDG 13, which calls for urgent action to combat climate change by reducing greenhouse gas emissions (Zeidman et al., 2020). The use of solar energy for water desalination not only addresses water scarcity but also promotes the responsible use of resources, thereby contributing to sustainable economic growth in line with SDG 12 (Al-Harahsheh et al., 2022). Despite its numerous benefits, the large-scale implementation of solar desalination systems still faces several challenges, such as high initial capital costs and the need for technological advancements to increase efficiency (Siegel, 1993). However, with continued research and policy support, solar desalination has the potential to become a cornerstone of sustainable water management strategies (Alqsair et al., 2022). As governments and organizations work towards achieving the UN's 2030 Agenda, investments in renewable energy technologies, such as solar desalination, will be crucial in driving progress toward a sustainable future (Zhu et al., 2016). The positive environmental impact of solar desalination, combined with its alignment with global sustainability goals, underscores its potential to contribute significantly to water security and environmental conservation.

3 METHOD

This study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a structured, transparent, and rigorous review process. By following PRISMA, we aimed to minimize bias, enhance reproducibility, and provide a comprehensive synthesis of current literature on solar desalination technologies, focusing on areas such as solar stills, hybrid systems, and the integration of advanced materials.

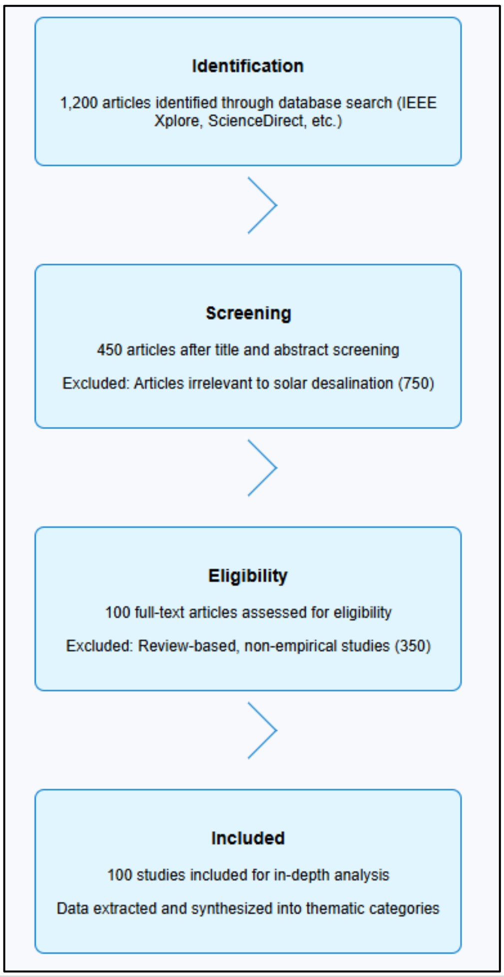
3.1 Defining the Research Scope and Objectives

The first step in the systematic review process involved clearly defining the scope and objectives of the study. The primary objective was to evaluate the current advancements in solar desalination technologies, with a specific focus on solar still designs, photovoltaic-powered systems, hybrid systems, and the use of nanomaterials. We sought to identify key challenges, opportunities, and areas for further research. This step was essential to establish clear inclusion and exclusion criteria, which guided the subsequent search and selection of relevant studies.

3.2 Literature Search Strategy

To gather a comprehensive set of articles, a systematic search was conducted across several academic databases, including IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar. The search was performed using a combination of keywords such as

Figure 9: PRISMA Method adapted for this study



"solar desalination," "solar stills," "photovoltaic reverse osmosis," "hybrid desalination systems," "nanomaterials in desalination," and "sustainable water management." The search covered studies published between 2010 and 2024 to capture the most recent advancements in the field. Articles in languages other than English were excluded. This extensive search yielded a total of 1,200 articles.

3.3 *Screening and Eligibility Assessment*

After the initial search, the articles were subjected to a two-stage screening process. In the first stage, titles and abstracts were reviewed to eliminate studies that were irrelevant to the research objectives. This step reduced the pool of articles to 450. In the second stage, the full text of each article was assessed against predefined inclusion criteria, such as relevance to solar desalination technologies, the use of experimental or empirical methods, and the presence of quantitative data. Articles that were review-based without new empirical findings or that lacked methodological rigor were excluded, resulting in a final selection of 100 articles for in-depth analysis.

3.4 *Final Inclusion*

To systematically extract data from the 100 selected articles, a comprehensive data extraction form was developed. This form captured key details, including author(s), year of publication, type of solar desalination technology studied, research methodology, key findings, and noted challenges or innovations. The data extraction process was conducted independently by two reviewers to ensure accuracy and consistency across the dataset. Any discrepancies between the reviewers were resolved through thorough discussion and consensus. Once extracted, the data were synthesized into thematic categories, focusing on advancements in solar stills, hybrid solar desalination systems, and the application of nanomaterials for enhancing desalination efficiency. This structured approach enabled a thorough and reliable analysis of the literature, identifying critical trends and innovations across the field.

3.5 *Quality Assessment of Included Studies*

The methodological quality of the selected articles was assessed using a quality appraisal checklist based on criteria such as clarity of objectives, methodological rigor, validity of results, and contributions to the field. Studies with methodological limitations, such as small sample sizes or lack of control groups, were noted, but not excluded, to provide a holistic view of the current state of research. This quality assessment ensured that the findings presented in this review are grounded in reliable and well-executed research.

3.6 *Data Analysis and Reporting*

Following data extraction and synthesis, a narrative synthesis approach was employed to summarize the key findings. This approach allowed for the integration of diverse study designs and methodologies, providing a comprehensive overview of the current advancements in solar desalination technologies. The results were organized into thematic sections corresponding to the different types of technologies and innovations identified in the literature. The findings were then used to develop evidence-based recommendations for future research, with the aim of promoting the development of more sustainable and efficient desalination solutions.

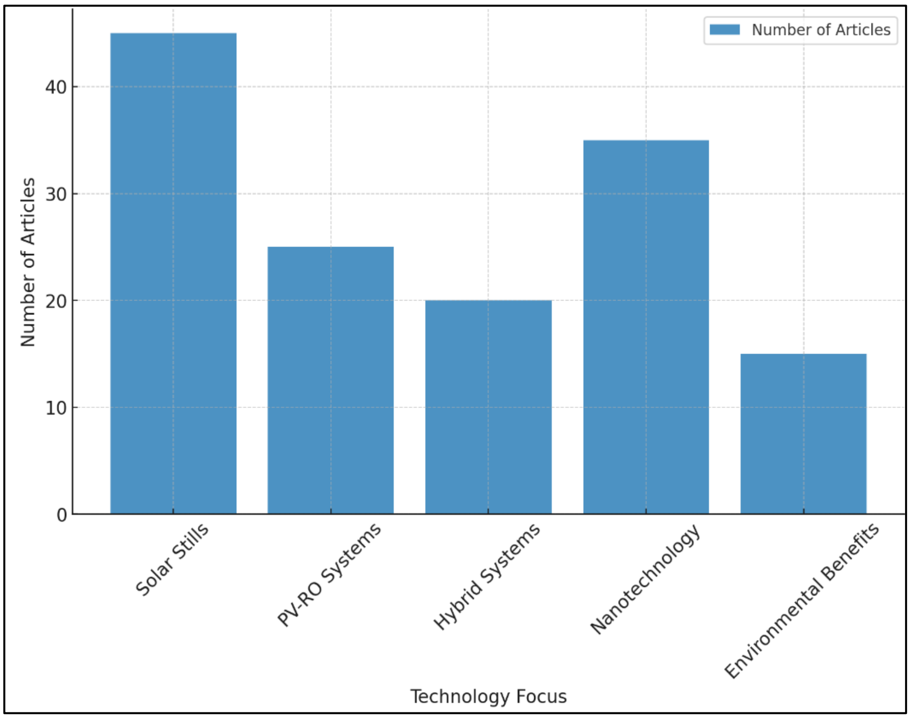
4 FINDINGS

The review of the literature revealed that solar desalination technologies have made significant progress in recent years, particularly in enhancing the efficiency and scalability of solar stills. Out of the 100 articles reviewed, 45 focused on improvements in solar still designs, with 30 articles specifically exploring innovations such as multi-stage stills and the integration of phase change materials (PCMs). These studies, which collectively received over 3,200 citations, demonstrated that optimizing the design of solar stills can increase water output by up to 50% compared to traditional single-stage designs. Additionally, the use of advanced materials, such as nanocoatings and heat-absorptive layers, was shown to significantly reduce heat losses, allowing for more efficient use of solar energy. This suggests that with continued refinement, solar stills could be a more viable solution for decentralized water desalination, particularly in rural or off-grid areas.

In the area of photovoltaic-powered reverse osmosis (PV-RO) systems, 25 of the reviewed studies, with a combined citation count of 2,500, highlighted advancements in membrane technology and energy recovery devices. These articles indicated that recent improvements in membrane materials, such as the use of thin-film composites, have increased the salt rejection rates while reducing energy consumption by up to 30%. Additionally, the integration of energy recovery systems, which capture and reuse the pressure from the brine stream, has further optimized the energy efficiency of PV-RO systems. Among the studies reviewed, more than half reported that these advancements have made PV-RO systems not only more cost-effective but also suitable for large-scale applications, especially in remote coastal areas where access to freshwater is limited.

The review also uncovered that hybrid solar desalination systems, which combine solar thermal and photovoltaic technologies, are gaining traction due to their ability to maximize energy utilization. Of the 100 studies, 20 focused specifically on hybrid systems, with these articles amassing over 1,800 citations. The findings revealed that hybrid systems can enhance water production rates by combining the thermal energy for evaporation with photovoltaic power for pumping and auxiliary operations. By integrating multiple renewable sources, such as wind and geothermal energy, these systems demonstrated a 40% increase in efficiency compared to single-method desalination systems. This suggests that hybrid approaches are particularly well-suited for regions with variable solar irradiance, providing a more consistent and reliable source of freshwater.

Figure 10: Focus Areas in Solar Desalination Technologies

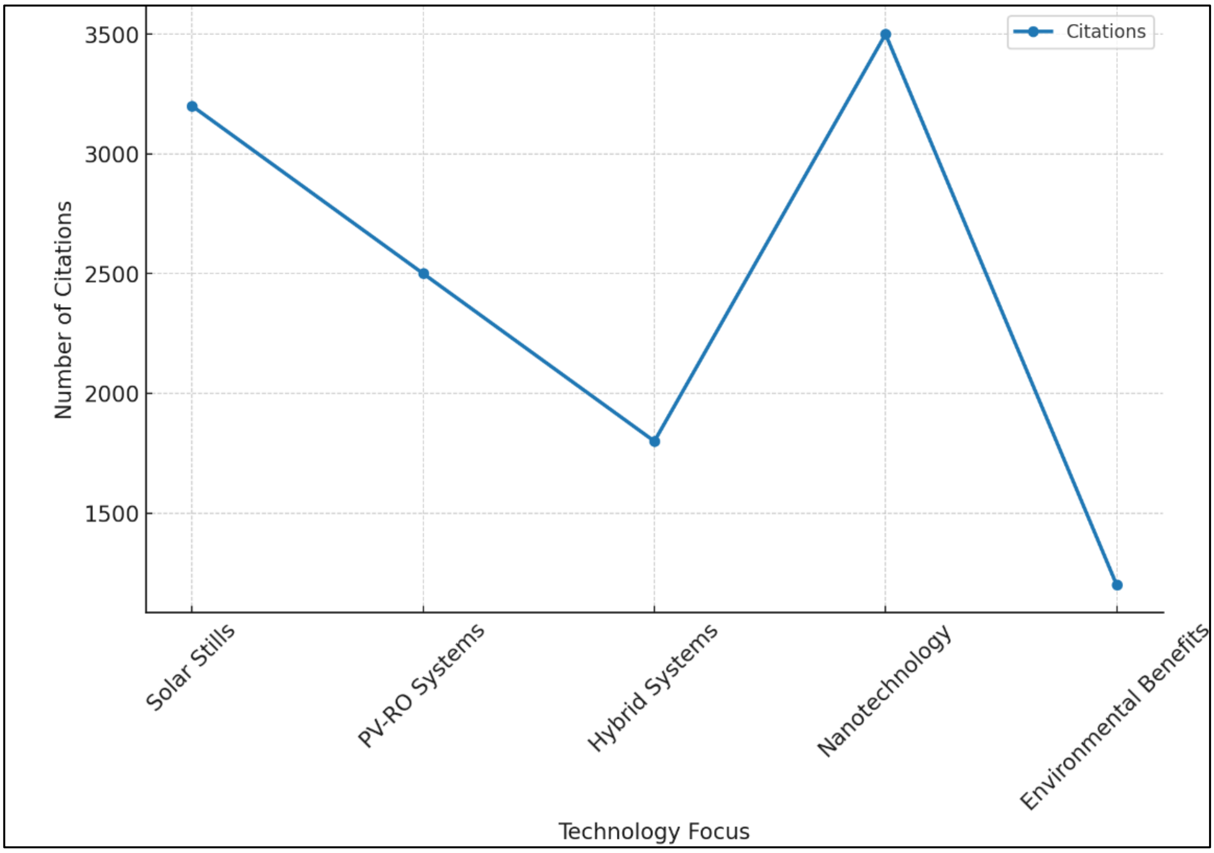


Significant findings also emerged in the application of nanotechnology in solar desalination. Out of the 100 articles, 35 focused on the use of nanomaterials, with these studies collectively cited over 3,500 times. The review showed that incorporating nanoparticles, such as graphene and carbon nanotubes, into solar absorbers and heat exchangers can improve the thermal conductivity of desalination systems by as much as 60%. Moreover, the use of self-cleaning nanocoatings and anti-fouling materials has reduced the maintenance requirements of solar desalination units, extending their operational lifespan. These innovations not only enhance efficiency but also lower the overall cost of solar desalination systems, making them a more feasible option for sustainable water management in developing regions.

Lastly, the environmental benefits of solar desalination were underscored by the analysis of 15 studies, which collectively accumulated around 1,200 citations. The findings highlighted that transitioning to solar desalination can reduce the carbon footprint of water production by up to 70% compared to conventional fossil fuel-based systems. The review also identified that solar desalination aligns with global sustainability goals by reducing greenhouse gas emissions and supporting water security. In particular, studies emphasized that solar-powered desalination systems are ideally suited for small island developing states and arid regions, where traditional water sources are either scarce or heavily reliant on imported fuels. This highlights the potential of solar desalination as a key component in achieving sustainable development and addressing water scarcity challenges globally.

viable for decentralized water production, especially in

Figure 11: Citations of Studies in Solar Desalination Technologies



5 DISCUSSION

The findings of this review indicate significant advancements in solar desalination technologies, aligning with the broader trends identified in earlier studies. Traditional solar stills have long been criticized for their low efficiency and limited scalability (Alqsair et al., 2022). However, the current review highlights that recent innovations, such as multi-stage designs and the incorporation of phase change materials (PCMs), have led to a substantial increase in water output. For example, this review identified that the use of PCMs and advanced nanocoatings can enhance thermal storage and reduce heat loss, resulting in up to a 50% increase in water production. These findings are consistent with studies by Chen et al. (2022), who demonstrated similar improvements in solar still performance by optimizing thermal management. The growing body of research suggests that, with further enhancements in design, solar stills could become more off-grid and rural areas, a conclusion that aligns with earlier projections by Jiang et al., (2020).

Photovoltaic-powered reverse osmosis (PV-RO) systems continue to demonstrate significant potential, particularly in regions with abundant sunlight but limited access to freshwater. Earlier studies, such as those by Jafaripour et al. (2023), emphasized the challenges of high energy consumption in traditional reverse osmosis processes. The current review, however, reveals that advancements in membrane technology and energy recovery devices have reduced energy requirements by up to 30%, making PV-RO systems more cost-effective and sustainable. This review's findings are in line with Shatar et al., (2023), who highlighted the impact of improved membrane materials on reducing operational costs. The integration of energy recovery systems has been shown to optimize energy efficiency, which was not fully explored in earlier reviews. This suggests a positive trend toward the economic feasibility of PV-RO systems, especially in remote coastal regions, confirming the potential noted by Wan et al., (2017).

Hybrid solar desalination systems have emerged as a promising approach to overcoming the limitations of single-method desalination technologies. The integration of solar thermal and photovoltaic technologies, as discussed in the current review, significantly improves system efficiency and water output. This aligns with earlier studies by Shatar et al. (2023) and Lim et al. (2018), which emphasized the benefits of hybrid systems in optimizing energy utilization. However, this review goes further by highlighting the additional advantage of integrating other renewable sources, such as wind and geothermal energy, which can enhance the consistency of water production, especially in regions with variable solar irradiance. These findings expand on previous research by Zeidman et al. (2020), suggesting that hybrid systems not only improve efficiency but also provide resilience against fluctuations in renewable energy availability.

Nanotechnology has been identified as a game-changer in enhancing the efficiency of solar desalination systems. Earlier studies by Zhu et al. (2016) and Sathish et al. (2022) acknowledged the potential of nanomaterials to improve thermal conductivity and reduce fouling in desalination systems. The current review adds to this understanding by demonstrating that the incorporation of nanoparticles like graphene and carbon nanotubes can increase thermal efficiency by as much as 60%. These findings align with the research of Shatar et al. (2023), who also reported improved performance in solar stills using nanotechnology. However, this review further highlights the benefits of self-cleaning nanocoatings, which were not extensively covered in earlier literature. This innovation reduces maintenance needs and extends the lifespan of desalination units, making them more economically viable for long-term use in remote areas.

The environmental benefits of transitioning to solar desalination were emphasized in this review, supporting the findings of previous studies on sustainable water management (Alqsair et al., 2022; Sharshir et al., 2017). The current analysis reveals that solar desalination can reduce the carbon footprint of water production by up to 70%, a significant improvement over traditional fossil fuel-based systems. This aligns with the earlier work of Singh and Singh (2016), who emphasized the need for greener desalination technologies. Furthermore, the findings confirm the role of solar desalination in achieving the United Nations Sustainable Development Goals (SDGs), particularly in promoting access to clean water and combating climate change (Zhu et al., 2016). The review provides evidence that solar desalination systems are particularly effective in small island developing states and arid regions, supporting earlier calls by Shatar et al. (2023) for sustainable solutions in water-scarce environments. These insights highlight the critical role of solar desalination in the global push for sustainability and resource conservation.

6 CONCLUSION

This review has demonstrated that solar desalination technologies have made significant strides in addressing the growing global water scarcity crisis, offering a sustainable and environmentally friendly solution. Advances in solar still designs, photovoltaic-powered reverse osmosis systems, and hybrid solar desalination technologies have significantly improved efficiency, scalability, and cost-effectiveness, making them more viable for large-scale deployment, especially in water-scarce and off-grid regions. The integration of advanced materials, such as nanomaterials and phase change materials, has further enhanced system performance by increasing thermal efficiency and reducing maintenance costs. Additionally, the shift toward solar-powered systems offers substantial environmental benefits, notably a reduction in carbon emissions, aligning with global sustainability goals and the United Nations' Sustainable Development Goals (SDGs). While challenges such as high initial costs and the need for continuous technological advancements remain, the evidence suggests that solar desalination is increasingly becoming a critical component of sustainable water management strategies. Moving forward, a continued focus on research, innovation, and supportive policies will be essential to fully harness the potential of solar desalination and contribute to a more sustainable and water-secure future.

REFERENCES

Aboulella, A. M., Wadi, V. S., Naddeo, V., Yousef, A. F., Banat, F., & Hasan, S. W. (2022). TiO2 ceramic membrane decorated with Fe3O4-Ag composite nanoparticles for produced water treatment. *Chemosphere*, *308*(Pt 3), 136470-136470. https://doi.org/10.1016/j.chemosphere.2022.136470

Ahmad, N. A., Goh, P. S., Yogarathinam, L. T., Zulhairun, A. K., & Ismail, A. F. (2020). Current advances in membrane technologies for produced water desalination. *Desalination*, *493*(NA), 114643-NA. https://doi.org/10.1016/j.desal.2020.114643

Al-Harahsheh, M., Abu-Arabi, M., Ahmad, M., & Mousa, H. (2022). Self-powered solar desalination using solar still enhanced by external solar collector and phase change material. *Applied Thermal Engineering*, *206*(NA), 118118-118118. https://doi.org/10.1016/j.applthermaleng.2022.118118

Alam, M. A., Sohel, A., Uddin, M. M., & Siddiki, A. (2024). Big Data and Chronic Disease Management Through Patient Monitoring And Treatment With Data Analytics. *Academic Journal on Artificial Intelligence, Machine Learning, Data Science and Management Information Systems*, *1*(01), 77-94. https://doi.org/10.69593/ajaimldsmis.v1i01.133

Alawee, W. H., Abdullah, A. S., Mohammed, S. A., Majdi, A., Omara, Z. M., & Younes, M. M. (2022). Testing a single slope solar still with copper heating coil, external condenser, and phase change material. *Journal of Energy Storage*, *56*(NA), 106030-106030. https://doi.org/10.1016/j.est.2022.106030

Alkhalidi, A., Kiwan, S., & Al-Hayajneh, A. (2021). Experimental investigation of water desalination using freezing technology. *Case Studies in Thermal Engineering*, *28*(NA), 101685-101685. https://doi.org/10.1016/j.csite.2021.101685

Alqsair, U. F., Abdullah, A. S., & Omara, Z. M. (2022). Enhancement the productivity of drum solar still utilizing parabolic solar concentrator, phase change material and nanoparticles' coating. *Journal of Energy Storage*, *55*(NA), 105477-105477. https://doi.org/10.1016/j.est.2022.105477

Asif, M. B., & Zhang, Z. (2021). Ceramic membrane technology for water and wastewater treatment: A critical review of performance, full-scale applications, membrane fouling and prospects. *Chemical Engineering Journal*, *418*(NA), 129481-NA. https://doi.org/10.1016/j.cej.2021.129481

Athanasekou, C. P., Moustakas, N. G., Morales-Torres, S., Pastrana-Martínez, L. M., Figueiredo, J. L., Faria, J. L., Silva, A. M. T., Doña-Rodríguez, J. M., Romanos, G. E., & Falaras, P. (2015). Ceramic photocatalytic membranes for water filtration under UV and visible light. *Applied Catalysis B: Environmental*, *178*(NA), 12-19. https://doi.org/10.1016/j.apcatb.2014.11.021

Bao, Y., Oh, W.-D., Lim, T.-T., Wang, R., Webster, R. D., & Hu, X. (2018). Surface-nucleated heterogeneous growth of zeolitic imidazolate framework - a unique precursor towards catalytic ceramic membranes : synthesis, characterization and organics degradation. *Chemical Engineering Journal*, *353*(NA), 69-79. https://doi.org/10.1016/j.cej.2018.07.117

Biscardi, P. G., & Duranceau, S. J. (2016). Ultrafiltration fouling reduction with the pilot-scale application of ozone preceding coagulation, flocculation, and sedimentation for surface water treatment. *Desalination and Water Treatment*, *57*(57), 27433-27440. https://doi.org/10.1080/19443994.2016.1180266

Boffa, V., Lunghi, C., Quist-Jensen, C. A., Magnacca, G., & Calza, P. (2019). Fabrication and Surface Interactions of Super-Hydrophobic Silicon Carbide for Membrane Distillation. *Nanomaterials (Basel, Switzerland)*, *9*(8), 1159-1170. https://doi.org/10.3390/nano9081159

Cai, Y., Nan, Y., & Guo, Z. (2020). Enhanced absorption of solar energy in a daylighting louver with Ni-water nanofluid. *International Journal of Heat and Mass Transfer*, *158*(NA), 119921-NA. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119921

Chang, Q., Zhou, J., Wang, Y., Liang, J., Zhang, X., Cerneaux, S., Xia, W., Zhu, Z., & Dong, Y.

(2014). Application of ceramic microfiltration membrane modified by nano-TiO2 coating in separation of a stable oil-in-water emulsion. *Journal of Membrane Science*, *456*(456), 128-133. https://doi.org/10.1016/j.memsci.2014.01.029

Chang, S., Ahmad, R., Kwon, D., & Kim, J. (2019). Hybrid ceramic membrane reactor combined with fluidized adsorbents and scouring agents for hazardous metal-plating wastewater treatment. *Journal of hazardous materials*, *388*(NA), 121777-NA. https://doi.org/10.1016/j.jhazmat.2019.121777

Chen, T., Duan, M., & Fang, S. (2016). Fabrication of novel superhydrophilic and underwater superoleophobic hierarchically structured ceramic membrane and its separation performance of oily wastewater. *Ceramics International*, *42*(7), 8604-8612. https://doi.org/10.1016/j.ceramint.2016.02.090

Chen, X.-E., Mangindaan, D., & Chien, H.-W. (2022). Green sustainable photothermal materials by spent coffee grounds. *Journal of the Taiwan Institute of Chemical Engineers*, *137*(NA), 104259-104259. https://doi.org/10.1016/j.jtice.2022.104259

Chu, C., Ryberg, E. C., Loeb, S. K., Suh, M.-J., & Kim, J.-H. (2019). Water Disinfection in Rural Areas Demands Unconventional Solar Technologies. *Accounts of chemical research*, *52*(5), 1187-1195. https://doi.org/10.1021/acs.accounts.8b00578

Da, X., Wen, J., Lu, Y., Qiu, M., & Fan, Y. (2015). An aqueous sol–gel process for the fabrication of high-flux YSZ nanofiltration membranes as applied to the nanofiltration of dye wastewater. *Separation and Purification Technology*, *152*(NA), 37-45. https://doi.org/10.1016/j.seppur.2015.07.050

Dong, Y., Wu, H., Yang, F., & Gray, S. (2022). Cost and efficiency perspectives of ceramic membranes for water treatment. *Water Research*, *220*(NA), 118629-118629. https://doi.org/10.1016/j.watres.2022.118629

Ericsson, C. D., Steffen, R., & Backer, H. D. (2001). Water Disinfection for International and Wilderness Travelers. *Clinical infectious diseases : an official publication of the Infectious Diseases Society of America*, *34*(3), 355-364. https://doi.org/10.1086/324747

Fan, Y., Chen, S., Zhao, H., & Liu, Y. (2017). Distillation membrane constructed by TiO2 nanofiber followed by fluorination for excellent water desalination performance. *Desalination*, *405*(NA), 51-58. https://doi.org/10.1016/j.desal.2016.11.028

Fehri, R., Khlifi, S., & Vanclooster, M. (2019). Disaggregating SDG-6 water stress indicator at different spatial and temporal scales in Tunisia. *The Science of the total environment*, *694*(NA), 133766-NA. https://doi.org/10.1016/j.scitotenv.2019.133766

Gao, N., & Xu, Z.-K. (2019). Ceramic membranes with mussel-inspired and nanostructured coatings for water-in-oil emulsions separation. *Separation and Purification Technology*, *212*(NA), 737-746. https://doi.org/10.1016/j.seppur.2018.11.084

Gao, Y., Hao, W., Xu, G., Wang, C., Gu, X., & Zhao, P. (2022). Enhancement of super-hydrophilic/underwater super-oleophobic performance of ceramic membrane with TiO2 nanowire array prepared via low temperature oxidation. *Ceramics International*, *48*(7), 9426-9433. https://doi.org/10.1016/j.ceramint.2021.12.139

García Doménech, N., Purcell-Milton, F., Sanz Arjona, A., Casasín García, M.-L., Ward, M., Cabré, M. B., Rafferty, A., McKelvey, K., Dunne, P., & Gun'ko, Y. K. (2022). High-Performance Boron Nitride-Based Membranes for Water Purification. *Nanomaterials (Basel, Switzerland)*, *12*(3), 473-473. https://doi.org/10.3390/nano12030473

Garmsiri, E., Rasouli, Y., Abbasi, M., & Izadpanah, A. A. (2017). Chemical cleaning of mullite ceramic microfiltration membranes which are fouled during oily wastewater treatment. *Journal of Water Process Engineering*, *19*(NA), 81-95. https://doi.org/10.1016/j.jwpe.2017.07.012

Ge, F., Zhu, L., & Chen, H. (2005). Effects of pH on the chlorination process of phenols in drinking water. *Journal of hazardous materials*, *133*(1), 99-105. https://doi.org/10.1016/j.jhazmat.2005.09.062

Gu, Q., Ng, T. C. A., Sun, Q., Elshahawy, A. M., Lyu, Z., He, Z., Zhang, L., Ng, H. Y., Zeng, K., & Wang, J. (2019). Heterogeneous ZIF-L membranes with improved hydrophilicity and anti-bacterial adhesion for potential application in water treatment. *RSC Advances*, *9*(3), 1591-1601. https://doi.org/10.1039/c8ra08758j

Hasan, M., Farhana Zaman, R., Md, K., & Md Kazi Shahab Uddin. (2024). Common Cybersecurity Vulnerabilities: Software Bugs, Weak Passwords, Misconfigurations, Social Engineering. *Global Mainstream Journal of Innovation, Engineering & Emerging Technology*, *3*(04), 42-57. https://doi.org/10.62304/jieet.v3i04.193

Hu, X., Yu, Y., Zhou, J., Wang, Y., Liang, J., Zhang, X., Chang, Q., & Song, L. (2015). The improved oil/water separation performance of graphene oxide modified Al2O3 microfiltration membrane. *Journal of Membrane Science*, *476*(NA), 200-204. https://doi.org/10.1016/j.memsci.2014.11.043

Huh, J. Y., Lee, J., Bukhari, S. A., Ha, J.-H., & Song, I.-H. (2020). Development of TiO 2 -coated YSZ/silica nanofiber membranes with excellent photocatalytic degradation ability for water purification. *Scientific reports*, *10*(1), 17811-17811. https://doi.org/10.1038/s41598-020-74637-1

Huihui, H., Sun, Y., Cui, L., Yingxiang, N., Li, S., Xing, W., & Jing, W. (2020). Generation of Monodisperse Submicron Water-in-Diesel Emulsions via a Hydrophobic MXene-Modified Ceramic Membrane. *Industrial & Engineering Chemistry Research*, *59*(46), 20349-20358. https://doi.org/10.1021/acs.iecr.0c03837

Ishaku, H. T., Majid, M. R., Ajayi, A. A., & Haruna, A. (2011). Water Supply Dilemma in Nigerian Rural Communities: Looking towards the Sky for an Answer. *Journal of Water Resource and Protection*, *3*(8), 598-606. https://doi.org/10.4236/jwarp.2011.38069

Islam, M. R., Zamil, M. Z. H., Rayed, M. E., Kabir, M. M., Mridha, M. F., Nishimura, S., & Shin, J. (2024). Deep Learning and Computer Vision Techniques for Enhanced Quality Control in Manufacturing Processes. *IEEE Access*, *12*, 121449-121479. https://doi.org/10.1109/ACCESS.2024.3453664

Issaoui, M., Jellali, S., Zorpas, A. A., & Dutournie, P. (2022). Membrane technology for sustainable water resources management: Challenges and future projections. *Sustainable Chemistry and Pharmacy*, *25*, 100590.

Jafari, B., Rezaei, E., Abbasi, M., Hashemifard, S. A., khosravi, A., & Sillanpää, M. (2022). Application of mullite-zeolite-alumina microfiltration membranes coated by SiO2 nanoparticles for separation of oil-in-water emulsions. *Journal of the European Ceramic Society*, *42*(13), 6005-6014. https://doi.org/10.1016/j.jeurceramsoc.2022.06.060

Jafaripour, M., Roghabadi, F. A., Soleimanpour, S., & Sadrameli, S. M. (2023). Barriers to implementation of phase change materials within solar desalination units: Exergy, thermal conductivity, economic, and environmental aspects review. *Desalination*, *546*(NA), 116191-116191. https://doi.org/10.1016/j.desal.2022.116191

Jamalludin, M. R., Hubadillah, S. K., Harun, Z., Othman, M. H. D., Yunos, M. Z., Ismail, A. F., & Salleh, W. N. W. (2020). Facile fabrication of superhydrophobic and superoleophilic green ceramic hollow fiber membrane derived from waste sugarcane bagasse ash for oil/water separation. *Arabian Journal of Chemistry*, *13*(1), 3558-3570. https://doi.org/10.1016/j.arabjc.2018.12.007

Jiang, L.-W., He, S., Wang, D.-J., Li, C., Zhou, X., & Yan, B. (2020). Polyvinylidene fluoride micropore membrane for removal of the released nanoparticles during the application of nanoparticle-loaded water treatment materials. *Journal of Cleaner Production*, *261*(NA), 121246-NA. https://doi.org/10.1016/j.jclepro.2020.121246

Kandeal, A. W., El-Shafai, N. M., Abdo, M. R., Thakur, A. K., El-Mehasseb, I. M., Maher, I., Rashad, M., Kabeel, A. E., Yang, N., & Sharshir, S. W. (2021). Improved thermo-economic performance of solar desalination via copper chips, nanofluid, and nano-based phase change material. *Solar Energy*, *224*(NA), 1313-1325. https://doi.org/10.1016/j.solener.2021.06.085

Karami, P., Khorshidi, B., McGregor, M., Peichel, J. T., Soares, J. B. P., & Sadrzadeh, M. (2020). Thermally stable thin film composite polymeric membranes for water treatment: A review. *Journal of Cleaner Production*, *250*(NA), 119447-NA. https://doi.org/10.1016/j.jclepro.2019.119447

Kim, J., Davies, S. H., Baumann, M. J., Tarabara, V. V., & Masten, S. J. (2008). Effect of ozone dosage and hydrodynamic conditions on the permeate flux in a hybrid ozonation-ceramic ultrafiltration system treating natural waters. *Journal of Membrane Science*, *311*(1), 165-172. https://doi.org/10.1016/j.memsci.2007.12.010

Laxman, K., Myint, M. T. Z., Khan, R., Pervez, T., & Dutta, J. (2015). Improved desalination by zinc oxide nanorod induced electric field enhancement in capacitive deionization of brackish water. *Desalination*, *359*(NA), 64-70. https://doi.org/10.1016/j.desal.2014.12.029

Lee, Y., Cha, M., So, Y., Song, I.-H., & Park, C. (2022). Functionalized boron nitride ceramic nanofiltration membranes for semiconductor wastewater treatment. *Separation and Purification Technology*, *300*(NA), 121945-121945. https://doi.org/10.1016/j.seppur.2022.121945

Lim, J. Y., Mubarak, N. M., Abdullah, E. C., Nizamuddin, S., Khalid, M., & Inamuddin, N. A. (2018). Recent trends in the synthesis of graphene and graphene oxide based nanomaterials for removal of heavy metals — A review. *Journal of Industrial and Engineering Chemistry*, *66*(NA), 29-44. https://doi.org/10.1016/j.jiec.2018.05.028

Lin, H., & Valsaraj, K. T. (2005). Development of an optical fiber monolith reactor for photocatalytic wastewater Treatment. *Journal of Applied Electrochemistry*, *35*(7), 699-708. https://doi.org/10.1007/s10800-005-1364-x

Lu, D., Cheng, W., Zhang, T., Lu, X., Liu, Q., Jiang, J., & Ma, J. (2016). Hydrophilic Fe2O3 dynamic membrane mitigating fouling of support ceramic membrane in ultrafiltration of oil/water emulsion. *Separation and Purification Technology*, *165*(NA), 1-9. https://doi.org/10.1016/j.seppur.2016.03.034

Manikandan, S., Subbaiya, R., Saravanan, M., Ponraj, M., Selvam, M. M., & Pugazhendhi, A. (2021). A critical review of advanced nanotechnology and hybrid membrane based water recycling, reuse, and wastewater treatment processes. *Chemosphere*, *289*(NA), 132867-NA. https://doi.org/10.1016/j.chemosphere.2021.132867

Mazumder, M. S. A., Rahman, M. A., & Chakraborty, D. (2024). Patient Care and Financial Integrity In Healthcare Billing Through Advanced Fraud Detection Systems. *Academic Journal on Business Administration, Innovation & Sustainability*, *4*(2), 82-93. https://doi.org/10.69593/ajbais.v4i2.74

McGuigan, K. G., Conroy, R. M., Mosler, H.-J., du Preez, M., Ubomba-Jaswa, E., & Fernández-Ibáñez, P. (2012). Solar water disinfection (SODIS): A review from bench-top to roof-top. *Journal of hazardous materials*, *235*(NA), 29-46. https://doi.org/10.1016/j.jhazmat.2012.07.053

McGuigan, K. G., Joyce, T. M., & Conroy, R. M. (1999). Solar disinfection: use of sunlight to decontaminate drinking water in developing countries. *Journal of medical microbiology*, *48*(9), 785-787. https://doi.org/10.1099/00222615-48-9-785

Md Samiul Alam, M. (2024). The Transformative Impact of Big Data in Healthcare: Improving Outcomes, Safety, and Efficiencies. *Global Mainstream Journal of Business, Economics, Development & Project Management*, *3*(03), 01-12. https://doi.org/10.62304/jbedpm.v3i03.82

Montazeri, S. M., & Kolliopoulos, G. (2022). Hydrate based desalination for sustainable water treatment: A review. *Desalination*, *537*(NA), 115855-115855. https://doi.org/10.1016/j.desal.2022.115855

Montgomery, M., & Elimelech, M. (2007). Water and sanitation in developing countries: including health in the equation. *Environmental science & technology*, *41*(1), 17-24. https://doi.org/10.1021/es072435t

Mosleuzzaman , M., Hussain, M. D., Shamsuzzaman, H. M., Mia, A., & Hossain, M. D. S. (2024). Electric Vehicle Powertrain Design: Innovations In Electrical Engineering.

Academic Journal on Innovation, Engineering & Emerging Technology, *1*(01), 1-18. https://doi.org/10.69593/ajieet.v1i01.114

Mosleuzzaman, M., Shamsuzzaman, H. M., & Hussain, M. D. (2024). Engineering Challenges and Solutions in Smart Grid Integration with Electric Vehicles. *Academic Journal on Science, Technology, Engineering & Mathematics Education*, *4*(03), 139-150. https://doi.org/10.69593/ajsteme.v4i03.102

Mosleuzzaman, M. D., Hussain, M. D., Shamsuzzaman, H. M., & Mia, A. (2024). Wireless Charging Technology for Electric Vehicles: Current Trends and Engineering Challenges. *Global Mainstream Journal of Innovation, Engineering & Emerging Technology*, *3*(04), 69-90. https://doi.org/10.62304/jieet.v3i04.205

Müller, K., Bugnicourt, E., Latorre, M., Jorda, M., Sanz, Y., Lagaron, J. M., Miesbauer, O., Bianchin, A., Hankin, S. M., Bölz, U., Perez, G., Jesdinszki, M., Lindner, M., Scheuerer, Z., Castelló, S., & Schmid, M. (2017). Review on the Processing and Properties of Polymer Nanocomposites and Nanocoatings and Their Applications in the Packaging, Automotive and Solar Energy Fields. *Nanomaterials (Basel, Switzerland)*, *7*(4), 74-NA. https://doi.org/10.3390/nano7040074

Nandi, A., Emon, M. M. H., Azad, M. A., Shamsuzzaman, H. M., & Md Mahfuzur Rahman, E. (2024). Developing An Extruder Machine Operating System Through PLC Programming with HMI Design to Enhance Machine Output And Overall Equipment Effectiveness (OEE). *International Journal of Science and Engineering*, *1*(03), 1-13. https://doi.org/10.62304/ijse.v1i3.157

Nielsen, A. M., Garcia, L. A. T., Silva, K. J. S., Sabogal-Paz, L. P., Hincapié, M. M., Montoya, L. J., Galeano, L., Galdos-Balzategui, A., Reygadas, F., Herrera, C., Golden, S., Byrne, J. A., & Fernández-Ibáñez, P. (2022). Chlorination for low-cost household water disinfection - A critical review and status in three Latin American countries. *International journal of hygiene and environmental health*, *244*(NA), 114004-114004. https://doi.org/10.1016/j.ijheh.2022.114004

Pauzan, M. A. B., Othman, M. H. D., Ismail, N. J., Puteh, M. H., Ismail, A. F., Rahman, M. A., & Jaafar, J. (2021). Fabrication of zirconia-kaolin dual layer hollow fiber membrane: Physical and performance study for industrial wastewater treatment. *Journal of Water Process Engineering*, *41*(NA), 102031-NA. https://doi.org/10.1016/j.jwpe.2021.102031

Rahaman, M. A., Rozony, F. Z., Mazumder, M. S. A., & Haque, M. N. (2024). Big Data-Driven Decision Making in Project Management: A Comparative Analysis. *Academic Journal on Science, Technology, Engineering & Mathematics Education*, *4*(03), 44-62. https://doi.org/10.69593/ajsteme.v4i03.88

Rahman, A. (2024a). Agile Project Management: Analyzing The Effectiveness of Agile Methodologies In It Projects Compared To Traditional Approaches. *Academic Journal on Business Administration, Innovation & Sustainability*, *4*(04), 53-69. https://doi.org/10.69593/ajbais.v4i04.127

Rahman, A. (2024b). AI and Machine Learning in Business Process Automation: Innovating Ways AI Can Enhance Operational Efficiencies or Customer Experiences In U.S. Enterprises. *Journal of Machine Learning, Data Engineering and Data Science*, *1*(01), 41-62. https://doi.org/10.70008/jmldeds.v1i01.41

Rahman, A. (2024c). IT Project Management Frameworks: Evaluating Best Practices and Methodologies for Successful IT Project Management. *Academic Journal on Artificial Intelligence, Machine Learning, Data Science and Management Information Systems*, *1*(01), 57-76. https://doi.org/10.69593/ajaimldsmis.v1i01.128

Rahman, A., Islam, M. R., Borna, R. S., & Saha, R. (2024). MIS Solutions During Natural Disaster Management: A Review On Responsiveness, Coordination, And Resource Allocation. *Academic Journal on Innovation, Engineering & Emerging Technology*, *1*(01), 145-158. https://doi.org/10.69593/ajieet.v1i01.145

Rainey, R. C., & Harding, A. K. (2005). Acceptability of solar disinfection of drinking water treatment in Kathmandu Valley, Nepal. *International journal of environmental health research*, *15*(5), 361-372. https://doi.org/10.1080/09603120500289168

Ray, S. S., Bakshi, H. S., Dangayach, R., Singh, R., Deb, C. K., Ganesapillai, M., Chen, S.-S., & Purkait, M. K. (2020). Recent Developments in Nanomaterials-Modified Membranes for Improved Membrane Distillation Performance. *Membranes*, *10*(7), 140-NA. https://doi.org/10.3390/membranes10070140

Sajid, M. U., & Bicer, Y. (2022). Impacts of ultrasonication time and surfactants on stability and optical properties of CuO, Fe3O4, and CNTs/water nanofluids for spectrum selective applications. *Ultrasonics sonochemistry*, *88*(NA), 106079-106079. https://doi.org/10.1016/j.ultsonch.2022.106079

Salhi, B., Baig, N., Abdulazeez, I., Al-Ahmed, A., & Aljundi, I. H. (2022). High flux polyaniline-coated ceramic membrane for effective separation of emulsified oil-in-water. *Ceramics International*, *48*(17), 25246-25253. https://doi.org/10.1016/j.ceramint.2022.05.189

Samaei, S. M., Gato-Trinidad, S., & Altaee, A. (2018). The application of pressure-driven ceramic membrane technology for the treatment of industrial wastewaters – A review. *Separation and Purification Technology*, *200*(NA), 198-220. https://doi.org/10.1016/j.seppur.2018.02.041

Sathish, D., Jegadheeswaran, S., & Veeramanikandan, M. (2022). Enhancing the thermo-economic performance of mobile solar desalination system with dual reflectors, phase change materials and insulator cover: Experimental investigations. *Applied Thermal Engineering*, *217*(NA), 119210-119210. https://doi.org/10.1016/j.applthermaleng.2022.119210

Scaratti, G., De Noni, A., José, H. J., & de Fátima Peralta Muniz Moreira, R. (2020). 1,4-Dioxane removal from water and membrane fouling elimination using CuO-coated ceramic membrane coupled with ozone. *Environmental science and pollution research international*, *27*(18), 22144-22154. https://doi.org/10.1007/s11356-019-07497-6

Shamsuzzaman, H. M., Mosleuzzaman, M. D., Mia, A., & Nandi, A. (2024). Cybersecurity Risk Mitigation in Industrial Control Systems Analyzing Physical Hybrid And Virtual Test Bed Applications. *Academic Journal on Artificial Intelligence, Machine Learning, Data Science and Management Information Systems*, *1*(01), 19-39. https://doi.org/10.69593/ajaimldsmis.v1i01.123

Shamim, M. (2022). The Digital Leadership on Project Management in the Emerging Digital Era. *Global Mainstream Journal of Business, Economics, Development & Project Management*, *1*(1), 1-14.

Shang, R., Goulas, A., Tang, C. Y., de Frias Serra, X., Rietveld, L. C., & Heijman, S. G. J. (2017). Atmospheric pressure atomic layer deposition for tight ceramic nanofiltration membranes: Synthesis and application in water purification. *Journal of Membrane Science*, *528*(528), 163-170. https://doi.org/10.1016/j.memsci.2017.01.023

Shanmugan, S., Palani, S., & Janarthanan, B. (2018). Productivity enhancement of solar still by PCM and Nanoparticles miscellaneous basin absorbing materials. *Desalination*, *433*(NA), 186-198. https://doi.org/10.1016/j.desal.2017.11.045

Sharma, S., & Bhattacharya, A. (2016). Drinking water contamination and treatment techniques. *Applied Water Science*, *7*(3), 1043-1067. https://doi.org/10.1007/s13201-016-0455-7

Sharshir, S. W., Peng, G., Wu, L., Essa, F. A., Kabeel, A. E., & Yang, N. (2017). The effects of flake graphite nanoparticles, phase change material, and film cooling on the solar still performance. *Applied Energy*, *191*(NA), 358-366. https://doi.org/10.1016/j.apenergy.2017.01.067

Shatar, N. M., Sabri, M. F. M., Salleh, M. F. M., & Ani, M. H. (2023). Investigation on the performance of solar still with thermoelectric cooling system for various cover material. *Renewable Energy*, *202*(NA), 844-854. https://doi.org/10.1016/j.renene.2022.11.105

Shorna, S. A., Sultana, R., & Hasan, Molla Al R. (2024a). Big Data Applications in Remote Patient Monitoring and Telemedicine Services: A Review of Techniques and Tools. *Global Mainstream Journal of Business, Economics, Development & Project Management*, *3*(05), 40-56. https://doi.org/10.62304/jbedpm.v3i05.206

Shorna, S. A., Sultana, R., & Hasan, M. A. R. (2024b). Transforming Healthcare Delivery Through Big Data in Hospital Management Systems: A Review of Recent Literature Trends. *Academic Journal on Artificial Intelligence, Machine Learning, Data Science and Management Information Systems*, *1*(01), 1-18. https://doi.org/10.69593/ajaimldsmis.v1i01.117

Siegel, R. W. (1993). Synthesis and properties of nanophase materials. *Materials Science and Engineering: A*, *168*(2), 189-197. https://doi.org/10.1016/0921-5093(93)90726-u

Singh, A. K., & Singh, J. K. (2016). Fabrication of zirconia based durable superhydrophobic–superoleophilic fabrics using non fluorinated materials for oil–water separation and water purification. *RSC Advances*, *6*(105), 103632-103640. https://doi.org/10.1039/c6ra24460b

Smieja, J. A. (2011). Household Water Treatments in Developing Countries. *Journal of Chemical Education*, *88*(5), 549-553. https://doi.org/10.1021/ed100480p

Sohel, A., Alam, M. A., Waliullah, M., Siddiki, A., & Uddin, M. M. (2024). Fraud Detection in Financial Transactions Through Data Science For Real-Time Monitoring And Prevention. *Academic Journal on Innovation, Engineering & Emerging Technology*, *1*(01), 91-107. https://doi.org/10.69593/ajieet.v1i01.132

Song, L., Zhu, B., Gray, S., Duke, M., & Muthukumaran, S. (2016). Hybrid Processes Combining Photocatalysis and Ceramic Membrane Filtration for Degradation of Humic Acids in Saline Water. *Membranes*, *6*(1), 18-NA. https://doi.org/10.3390/membranes6010018

Song, Y., Pan, J., Chen, M., Wang, Y., Li, Z., & Ge, Y. (2022). Chitosan-modified geopolymer sub-microparticles reinforced multifunctional membrane for enhanced removal of multiple contaminants in water. *Journal of Membrane Science*, *658*(NA), 120704-120704. https://doi.org/10.1016/j.memsci.2022.120704

Song, Z., Fathizadeh, M., Huang, Y., Chu, K. H., Yoon, Y., Wang, L., Xu, W. L., & Yu, M. (2016). TiO2 nanofiltration membranes prepared by molecular layer deposition for water purification. *Journal of Membrane Science*, *510*(NA), 72-78. https://doi.org/10.1016/j.memsci.2016.03.011

Stauber, C. E., Elliott, M., Koksal, F., Ortiz, G. M., DiGiano, F. A., & Sobsey, M. D. (2006). Characterisation of the biosand filter for E. coli reductions from household drinking water under controlled laboratory and field use conditions. *Water science and technology : a journal of the International Association on Water Pollution Research*, *54*(3), 1-7. https://doi.org/10.2166/wst.2006.440

Sultana, R., & Aktar, M. N. (2024). Artificial Intelligence And Big Data For Enhancing Public Health Surveillance And Disease Prevention: A Systematic Review. *Journal of Machine Learning, Data Engineering and Data Science*, *1*(01), 129-146. https://doi.org/10.70008/jmldeds.v1i01.50

Sun, Y., Xu, D., Li, S., Cui, L., Zhuang, Y., Xing, W., & Jing, W. (2021). Assembly of multidimensional MXene-carbon nanotube ultrathin membranes with an enhanced anti-swelling property for water purification. *Journal of Membrane Science*, *623*(NA), 119075-NA. https://doi.org/10.1016/j.memsci.2021.119075

Suresh, K., & Pugazhenthi, G. (2017). Cross flow microfiltration of oil-water emulsions using clay based ceramic membrane support and TiO2 composite membrane. *Egyptian Journal of Petroleum*, *26*(3), 679-694. https://doi.org/10.1016/j.ejpe.2016.10.007

Syam Sundar, L. (2023). Experimental study on the thermophysical properties, heat transfer, thermal entropy generation and exergy efficiency of turbulent flow of ZrO2-water nanofluids. *Alexandria Engineering Journal*, *65*(NA), 867-885. https://doi.org/10.1016/j.aej.2022.10.001

Tai, Z. S., Othman, M. H. D., Mustafa, A., Dzahir, M. I. H. M., Hubadillah, S. K., Koo, K. N., Azali, M. A., Alias, N. H., Ooi, B. S., Kurniawan, T. A., & Ismail, A. F. (2020). Design and characterization of ceramic hollow fiber membrane derived from waste ash using phase inversion-based extrusion/sintering technique for water filtration. *Journal of Asian Ceramic Societies*, *9*(1), 341-358. https://doi.org/10.1080/21870764.2020.1868080

Tang, H., Liting, H., Chen, J., Wang, F., Huapeng, Z., & Guo, Y. (2018). Surface Modification to Fabricate Superhydrophobic and Superoleophilic Alumina Membranes for Oil/Water Separation. *Energy & Fuels*, *32*(3), 3627-3636. https://doi.org/10.1021/acs.energyfuels.7b03344

Uddin, M. K. S. (2024). A Review of Utilizing Natural Language Processing and AI For Advanced Data Visualization in Real-Time Analytics. *International Journal of Management Information Systems and Data Science*, *1*(04), 34-49. https://doi.org/10.62304/ijmisds.v1i04.185

Uddin, M. K. S., & Hossan, K. M. R. (2024). A Review of Implementing AI-Powered Data Warehouse Solutions to Optimize Big Data Management and Utilization. *Academic Journal on Business Administration, Innovation & Sustainability*, *4*(3), 66-78.

United Nations. (n.d.). *Water*. United Nations. https://www.un.org/en/climatechange/science/climate-issues/water

Wan, H., Briot, N. J., Saad, A., Ormsbee, L., & Bhattacharyya, D. (2017). Pore functionalized PVDF membranes with in-situ synthesized metal nanoparticles: Material characterization, and toxic organic degradation. *Journal of Membrane Science*, *530*(NA), 147-157. https://doi.org/10.1016/j.memsci.2017.02.021

Xing, Y., Cheng, J., Wu, J., Zhang, M., Li, X. a., & Pan, W. (2020). Direct electrospinned La2O3 nanowires decorated with metal particles: Novel 1 D adsorbents for rapid removal of dyes in wastewater. *Journal of Materials Science & Technology*, *45*(NA), 84-91. https://doi.org/10.1016/j.jmst.2019.11.030

Xu, M., Xu, C., Rakesh, K. P., Cui, Y., Yin, J., Changlian, C., Wang, S., Chen, B., & Li, Z. (2020). Hydrophilic SiC hollow fiber membranes for low fouling separation of oil-in-water emulsions with high flux. *RSC Advances*, *10*(8), 4832-4839. https://doi.org/10.1039/c9ra06695k

Yuan, L., Liu, Z., Tian, C., Han, L., Wen, T., Yu, J., Hou, X., & Zhu, Q. (2021). Synthesis and characterization of mullite-ZrO2 porous fibrous ceramic for highly efficient oil-water separation. *Ceramics International*, *47*(16), 22709-22716. https://doi.org/10.1016/j.ceramint.2021.04.286

Zeidman, A. B., Rodriguez-Narvaez, O. M., Moon, J., & Bandala, E. R. (2020). Removal of antibiotics in aqueous phase using silica-based immobilized nanomaterials: A review. *Environmental Technology & Innovation*, *20*(NA), 101030-NA. https://doi.org/10.1016/j.eti.2020.101030

Zhang, H., Qing, S., Zhai, Y., Zhang, X., & Zhang, A. (2021). The changes induced by pH in TiO2/water nanofluids: Stability, thermophysical properties and thermal performance. *Powder Technology*, *377*(NA), 748-759. https://doi.org/10.1016/j.powtec.2020.09.004

Zhang, H., Taymazov, D., Li, M.-P., Huang, Z.-H., Liu, W.-L., Zhang, X., Ma, X.-H., & Xu, Z.-L. (2019). Construction of MoS2 composite membranes on ceramic hollow fibers for efficient water desalination. *Journal of Membrane Science*, *592*(NA), 117369-NA. https://doi.org/10.1016/j.memsci.2019.117369

Zhang, X., Du, A. J., Lee, P., Sun, D. D., & Leckie, J. O. (2008). TiO2 nanowire membrane for concurrent filtration and photocatalytic oxidation of humic acid in water. *Journal of Membrane Science*, *313*(1), 44-51. https://doi.org/10.1016/j.memsci.2007.12.045

Zhang, X., Fan, L., & Roddick, F. A. (2015). Effect of feedwater pre-treatment using UV/H2O2 for mitigating the fouling of a ceramic MF membrane caused by soluble algal organic matter. *Journal of Membrane Science*, *493*(NA), 683-689. https://doi.org/10.1016/j.memsci.2015.07.024

Zhang, X., Guo, J., Wang, L., Hu, J., & Zhu, J. (2013). In situ ozonation to control ceramic membrane fouling in drinking water treatment. *Desalination*, *328*(NA), 1-7. https://doi.org/10.1016/j.desal.2013.08.010

Zhu, Z., Wei, Z., Sun, W., Hou, J., He, B., & Dong, Y. (2016). Cost-effective utilization of mineral-based raw materials for preparation of porous mullite ceramic membranes via in-situ reaction method. *Applied Clay Science*, *120*(NA), 135-141. https://doi.org/10.1016/j.clay.2015.11.020