

Research Article

Toward Sustainable Solar Interfacial Desalination in the Gulf Region: Empirical Testing and Cost-Effectiveness Modeling of a Bacterial Cellulose–Silica Composite with Photothermal Iron Oxide

Jinseok An

Independent Researcher, Seoul Innovation Research Institute, South Korea

Email: js.an070516@gmail.com

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Abstract

This study examines the feasibility of a small-scale, solar-driven desalination approach as a complementary solution to addressing global freshwater scarcity, with particular relevance to the Gulf region. While large-scale thermal and reverse osmosis plants remain the backbone of water supply, they impose high capital, energy, and environmental costs. To address these issues, a low-cost prototype was developed using silica-agar composite reinforced with bacterial cellulose and biochar, with an iron oxide surface layer to enhance solar absorption. Laboratory experiments demonstrated substantial water uptake and localized heating, but also revealed constraints in evaporation efficiency due to continuous cooling at the liquid-air interface. The process of condensation emerged as the critical bottleneck, as only a small fraction of the generated vapor was transformed back into liquid. An economic assessment using the levelized cost of water suggest economic viability of the prototype that can be manufactured at low cost with no additional energy input. Further scenario sensitivity analysis indicates larger hydrophilic condensing surfaces, improved drainage and seals, and longer service life could increase both the performance efficiency and cost effectiveness when scaled. Overall, the prototype presents a promising potential for sustainable desalination in hot, high-radiance regions.

Keywords: Solar Desalination, Interfacial Evaporation, Water Security, Gulf Region, Levelized Cost of Water, Bio-Inspired Materials.

1. Introduction

Access to safe drinking water remains one of the most pressing global challenges, with one in four of the world's population, amounting to over 2.1 billion, lacking access to safely managed drinking water (UNICEF, 2025; WHO, 2025). While universal and equitable access has been recognized by the United Nations as a human right and codified in Sustainable Development Goal 6 (UN-Water, 2024), persistent shortfalls in clean water access continue to adversely affect health outcomes, educational attainment, and economic participation, while disproportionately burdening children and women who devote substantial time to water collection (Omer, 2025). The growing industrial demand for water boosts the need for new freshwater production methods, especially in the desalination sector, but for this new investment, tools and technologies are required. These efforts are not without perks, as the economic benefits are predicted to outweigh the costs. According to the World Resources Institute, every single dollar invested in water access and sanitation yields an average return of US\$6.80 (Strong and Kuzma, 2020; Hutton, 2022). Climate change, pollution, and sea-level rise further strain already limited freshwater sources and complicates infrastructure planning (World Economic Forum, 2024).

Against this backdrop, desalination has attracted considerable policy and scholarly interest as a promising strategy to alleviate freshwater scarcity. Global installed desalination capacity has rapidly increased, reaching an estimated 36.1 billion cubic meters annually in 2022 (Eyl-Mazzega and Cassignol, 2022; Wood, 2024). Scholarly interest has mirrored this growth, with bibliometric analyses showing exponential growth in desalination research since 2008, particularly in areas such as reverse osmosis, thermal approaches, and renewable-energy desalination (Zapata-Sierra *et al.*, 2021). Recent scholarship emphasizes sustainable desalination methods given the high energy intensity, financial cost, and environmental consequences that

accompany large-scale desalination processes (Ayaz *et al.*, 2022; Padmanathan, 2022; Wood, 2024). Typically, freshwater produced from desalination is more expensive than that from conventional sources, such as pumping and treating groundwater. However, the cost of desalinated water has been steadily decreasing, while the costs associated with conventional water sources have been rising as they become less accessible. For instance, extracting groundwater from depths of 300 meters can require 1 kilowatt-hour per cubic meter (kWh/m³), and additional treatment is often necessary to address pollution (Pistocchi *et al.*, 2020). For desalination using the most widely deployed technique of reverse osmosis, Hwang and colleagues (2016) estimate the energy consumption to range between 2.5 and 4.0 kWh/m³, making it increasingly comparable in cost and energy efficiency to conventional pumping. Along with the high cost associated with initial investment and ongoing costs of water processing in desalination, critics of desalination also highlight its adverse effects on the environment and marine life, including fossil fuel overuse, greenhouse gas emissions, and the discharge of concentrated brine (Dongare *et al.*, 2017; Sirota *et al.*, 2023).

As one of the most water-scarce regions of the world, the Gulf region has been a central hub of intense desalination (Purnama, 2021). Long-term assessments of the Gulf Cooperation Council countries describe a hydrologic regime characterized by minimal rainfall, meager and overdrawn groundwater reserves, inadequate strategic storage, and increasing levels of water consumption driven by rapid urbanization and population growth (Al-Harashsheh and Salameh, 2023). As these challenges prevail, seawater desalination has become central to ensuring sustainable water security. The warm, semi-enclosed Arabian and Persian Gulf, characterized by its naturally high salinity and temperature, offers favorable conditions for desalination. Conventional thermal technologies, such as multi-stage flash and multi-effect distillation, have delivered reliable volumes of clean water; however, this reliance on desalination has come at a significant cost in terms of energy use and environmental impact (Lattemann and Höpner, 2008; Padmanathan, 2022). Brine discharges, residual oxidants, thermal plumes, and corrosion metals from large-scale coastal desalination facilities accumulate and stress near-field ecosystems in ways that are not easily mitigated by open-ocean circulation, particularly in the semi-enclosed Gulf basin (Lattemann and Höpner, 2008; Dawoud and Mulla, 2012; Purnama, 2021).

In response, regional and industry roadmaps on sustainable water supply, applying desalination increasingly emphasize two levers-decarbonizing the energy input and reducing energy consumption-while encouraging innovation that lowers costs and minimizes environmentally harmful discharges (Padmanathan, 2022). Within this context, interfacial solar evaporation-based desalination has emerged as a promising alternative. Unlike reverse osmosis, solar-driven evaporation leverages naturally available solar energy to drive evaporation directly at the liquid-air interface, thereby reducing energy demands and the concerns over marine pollution and environmental degradation (Zhang *et al.*, 2021; Dong *et al.*, 2023). Yet, the efficiency of interfacial solar evaporation is often limited by the high energy required to break hydrogen bonds between water molecules and the ubiquitous salts present in seawater, which suppress the evaporation rate and leave residue on the surface during evaporation (Yu *et al.*, 2024). To overcome these constraints, careful design of material structures is necessary to enhance capillary water transport, maximize sunlight absorption, and manage salinity effects.

Over the past decade, several material innovations have emerged to address challenges related to capillary transport, fouling, and heat management in desalination processes. Notable developments include iron oxide photothermal coatings, hydrophilic silica-diatomite scaffolds, bacterial cellulose wicks, and biochemical substrates. Research indicates that spectrally dark photothermal coatings made from iron oxide can elevate interfacial temperatures and distribute heat uniformly across porous supports (Bai *et al.*, 2022). Additionally, hydrophilic scaffolds constructed from silica and diatomite enhance capillary transport and texturing, which in turn improves wetting and light-trapping capabilities (Alsar *et al.*, 2020; Song *et al.*, 2021; Zdarta and Jesionowski, 2022). Bacterial cellulose acts as a conformal, mechanically robust wick, offering exceptional hydrophilicity and chemical resistance (Chawla *et al.*, 2009; Lahiri *et al.*, 2021). Biochar, on the other hand, provides hierarchical porosity that facilitates water storage, tolerates salt cycling, and helps moderate convective heat loss (Zhang *et al.*, 2021; Dong *et al.*, 2023). Concurrent developments in nanophotonics-enabled solar membrane distillation demonstrate how the interfacial solar heat can be harnessed in compact, off-grid systems (Boyd, 2017; Dongare *et al.*, 2017). This reinforces the viability of low-energy desalination without relying on grid energy suitable for household or community applications when designed for manufacturability and modular replication.

Innovation in desalination has extended beyond membrane technology. Recent studies emphasize the importance of optimizing condensers and ensuring sealed vapor pathways. Effective ion-exchangeable

mineral additives can significantly reduce the evaporation enthalpy of seawater at the interface, allowing it to evaporate faster than freshwater under sunlight, provided the surface chemistry is adjusted to weaken hydration shells (Yu *et al.*, 2024). The literature on system integration highlights that achieving optimal yield depends not only on generating vapor but also on efficiently removing latent heat (Liu *et al.*, 2023). Together, these developments illustrate not only the growing role of desalination in global water security, but also the increasing scholarly and policy emphasis on renewable energy integration and small-scale alternatives focused on sustainability.

Building on these insights, this study assesses the effectiveness and economic viability of a low-cost, energy-efficient desalination device that combines a silica–agar scaffold with a bacterial-cellulose wick, augmenting interfacial performance through either a thin iron oxide coating or a subsurface biochar layer. The hypothesis posits that a composite desalination structure integrating silica, diatomite, agar, and bacterial cellulose, combined with either iron oxide or biochar, can increase evaporation efficiency and freshwater yield compared to unmodified control while remaining simple to replicate and manufacture and inexpensive to deploy. Laboratory experiments will quantify water uptake dynamics, interfacial temperature behavior, evaporation flux, and condensation across various material combinations to identify performance-cost trade-offs and optimal silica–diatomite proportions for capillary supply and salt management. In parallel, a cost-benefit analysis based on a levelized cost of water (LCOW) framework will evaluate the economic viability and cost-benefit implications of scaling and implementing the developed prototype in the Gulf region.

Potential contributions of this study are threefold: First, empirical results demonstrate that a silica–agar–cellulose architecture, selectively enhanced with iron oxide or biochar, can rebalance capillary supply and interfacial heating to mitigate common loss mechanisms in solar evaporation systems. Second, a cost-benefit analysis based on the LCOW modeling reveals both the potential and challenges in translating small-scale laboratory results to assess the economic viability when scaled and implemented in practice. Third, by demonstrating the potential of developing an effective device producing with low-cost, readily available materials, when meticulously configured to address interfacial heat-transfer and vapor-recovery constraints, can produce potable water, the study underscores the capacity of small-scale solar desalination devices to complement conventional, large, centralized Gulf facilities while simultaneously reducing greenhouse-gas emissions and local discharge footprints across the Gulf and other water-stressed regions.

The article proceeds by detailing materials and methods, including device fabrication, experimental protocols, and the cost-benefit analysis model. The following section presents empirical findings from a series of laboratory experiments assessing the evaporation, condensation, and levelized costs for different combinations of options. I then discuss the implications of the laboratory results and practical considerations for scaling and implementation in light of recent literature and conclude with suggestions for future research.

2. Materials and Methods

2.1. Materials and Preparation

Silica, diatomite, and agar were selected as primary structural components for the desalination device. To evaluate the effects of different material compositions on water absorption and evaporation performance, food-grade diatomite (JJS Minerals Peru S.A.C., Lima, Belgium) and silica powder (Dental Silica, Solvay, Collonges au Mont d'Or, France) were mixed in varying proportions (see Table 1). Each powder mixture was dispersed into 100 milliliters of a 1% agar solution, which served as a gel binder and was then poured into a 50-milliliter conical mold containing an inner 15 mL water-filled tube to form a hollow cylindrical design suitable for capillary wicking.

Table 1. Ratios of silica and diatomite used in the samples.

Sample	#1	#2	#3	#4
SiO ₂ (g)	10	5	2.5	0
Diatomite (g)	0	5	7.5	10

Bacterial cellulose was produced by cultivating *Gluconacetobacter xylinus* (KACC 12367) in a glucose–yeast medium. The culture medium consisted of 10 grams of glucose and 1 gram of yeast extract in 100 milliliters of distilled water, sterilized by autoclaving at 121 °C for 15 minutes. Cylindrical silica–diatomite–agar scaffolds were immersed in the culture broth and incubated at 37 °C for one week to allow in situ cellulose growth on the scaffold surface. After incubation, the scaffolds were washed with distilled water, dried at

50 °C, and used for subsequent absorption and evaporation tests. In a modified design, cellulose was also cultured on flat agar-silica substrates in petri dishes to improve adhesion. The cellulose layers were purified by immersion in 0.05 molar sodium hydroxide, followed by repeated rinsing in distilled water, and subsequently integrated with the cylindrical silica-agar-diatomite composites to form a hydrophilic wick.

2.2. Preparation of Parabolic Structures with Iron Oxide

To investigate the effects of photothermal enhancement, iron oxide was synthesized by coprecipitating iron (II) chloride and iron (III) chloride in a one-to-four molar ratio, with ammonium hydroxide added dropwise until a black precipitate formed. The precipitate was collected magnetically, washed with distilled water, and dried. A hemispherical scaffold composed of silica and agar was coated evenly with iron oxide to form a parabolic structure, which was subsequently joined to the cylindrical scaffold using an additional silica-agar matrix.

Supplementary photothermal and absorptive additives were introduced in selected configurations. Iron (II, III) oxide was synthesized via coprecipitation of ferric and ferrous chloride solutions (molar ratio 4:1), with ammonium hydroxide added dropwise until a black suspension was formed. The resulting particles were magnetically separated, rinsed with distilled water, and evenly distributed across the surface of the agar-silica structures before drying. In a parallel series, biochar was incorporated (2g per structure) to enhance porosity, water uptake, and thermal regulation.

2.3. Device Assembly and Design

Early prototypes combined a cylindrical scaffold with a parabolic cap intended to enhance light concentration and evaporation. However, interfacial cracking between the two components disrupted water transport and vapor pathways, resulting in reduced performance. To overcome these limitations, the design was simplified by inverting the cylindrical structure and incorporating a disk surface treated with iron (II, III) oxide. This modification ensured more direct vapor release, reduced sealing challenges, and improved thermal uniformity. In addition, a rigid base plate was incorporated to stabilize the bacterial cellulose layer, which otherwise detached during extended operation. The final configuration is illustrated in Figure 1, which presents the seawater desalination plant model constructed from silica-agar composites, diatomite, bacterial cellulose, and iron oxide or biochar additions.

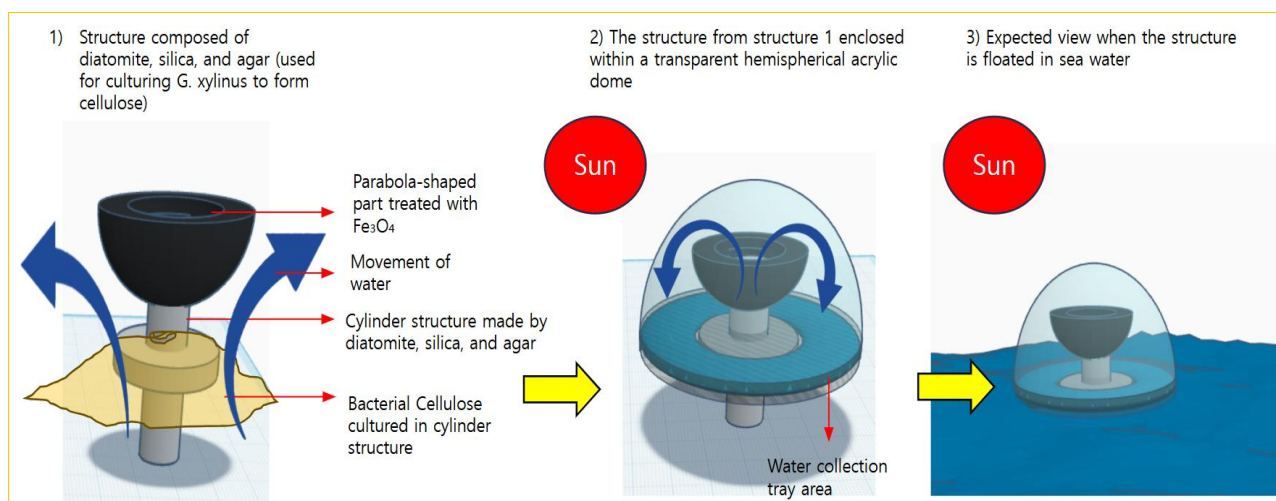


Figure 1. Schematic of the device designed for application in seawater desalination via evaporation.

2.4. Experiments and Measurement

Performance of the assembled devices was evaluated through a series of controlled laboratory experiments. Samples were placed in petri dishes containing measured volumes of distilled water or a 3.5 percent sodium chloride solution. Illumination was provided by a light source of 1500 lux, with surface and ambient temperatures monitored using an infrared thermal camera and digital thermometers. Experimental runs varied in duration from three to seven hours, with mass and volume measurements recorded at intervals ranging from ten minutes to one hour.

For freshwater yield water uptake is quantified by measuring mass gain of the structure, while evaporation and condensation is assessed from changes in water mass over six-hour lamp-heated trials and shorter 4.5-hour runs. Condensed water is collected and analyzed for salinity, and its biological safety was probed using

a brine-shrimp hatchability assay. Dissolved oxygen is measured in both the control and treated samples to assess water quality. Surface temperatures and thermal distribution is monitored using an infrared camera. All experiments are performed in triplicate where feasible to ensure reproducibility.

To evaluate the quality or purity of the condensed water, a biological viability assay is used. Brine shrimp (*Artemia salina*) eggs (0.5 grams) are introduced into collected samples. After 24 hours of incubation, 2 milliliters of water were sampled, and hatched larvae were counted microscopically. The test is repeated across five replicates, and average hatch rates were compared against those in a control group incubated in distilled water.

2.5. Cost-Effectiveness Analysis

To evaluate the economic viability of the proposed device, a cost-effectiveness analysis was conducted using the Levelized Cost of Water (LCOW) framework. LCOW provides a standardized measure of cost per unit volume of freshwater produced (USD/m³), enabling straightforward comparison across technologies that differ in scale, design, and lifetime (Kruse *et al.*, 2025). Its relative simplicity has made it a widely adopted metric in the desalination and water treatment literature, particularly where more complex cost-benefit analyses or return-on-investment calculations are difficult to apply or risk overlooking non-market benefits. In practice, LCOW has been applied to a range of desalination settings, including both hypothetical scenarios and real-world case studies. For instance, Colciaghi *et al.*, (2022) and Lugo *et al.*, (2025) modeled solar-energy-powered seawater desalination systems to assess their cost competitiveness under different operating assumptions, while Kaya *et al.*, (2019) applied LCOW in the Emirate of Abu Dhabi to evaluate the long-run viability of integrating solar-powered systems into an energy-intensive, desalination-dependent water economy. These applications illustrate the usefulness of LCOW in benchmarking both conventional and experimental approaches.

The LCOW in this study was calculated using the standard expression:

$$LCOW (\$/m^3) = \frac{\text{Annualized CAPEX} + \text{Annual OPEX}}{\text{Annual recovered water}}$$

Where the numerator accounts for the annualized capital expenditure (CAPEX) and operation and maintenance (OPEX) costs, and the denominator represents the annual quantity of freshwater recovered. Annualization of capital cost was performed using a capital recovery factor (CRF) that incorporates both the discount rate and device lifetime.

For the base case, assumptions are tailored to reflect small-scale solar desalination under Gulf region conditions (Table 2). The device is inexpensive to build at laboratory scale, with an estimated initial production cost of one laboratory-scale device of approximately USD 1. To compare across years, the cost is annualized over the expected lifetime. A two-year lifetime reflects the fragility of early, student-fabricated structures, consistent with preliminary durability observations, and therefore intentionally biases capital recovery against the design. A five percent real discount rate lies within the range commonly used in water and energy analyses and harmonizes with rates employed in levelized cost studies for desalination projects (Kaya *et al.*, 2019; Kruse *et al.*, 2025). Although the device itself is simple, real-world operation entails recurring costs. As such, operating costs are expected to exceed capital costs due to maintenance needs such as salt removal, inspection for cracking, and general performance monitoring; while hourly wage for maintenance work differs across the region, a conservative estimate of maintenance costs is set at USD 1,000 per year. Given average solar irradiance in the Gulf, daily operation was assumed to last 8 hours across 300 days per year. Sensitivity analyses are conducted to test the effect of varying condenser efficiency and extending device lifetime on the LCOW modeling outcomes.

Table 2. Input assumptions for LCOW calculation.

Parameter	Symbol	Value	Unit	Notes
Capital expenditure	CAPEX	1	USD	Per lab-scale device
Operating expenditure	OPEX	10	USD/year	Maintenance, salt removal, crack checks
Lifetime	n	2	Years	Base case assumption
Discount rate	r	5	%	Commonly adopted (Kaya <i>et al.</i> , 2019; Kruse <i>et al.</i> , 2025)
Operational days	d	300	Days/year	Sunlight days in Gulf (Ata, 2025)
Sunlight hours	h	8	Hours/day	Lower bound of Gulf range

3. Results

3.1. Water Uptake, Evaporation, and Condensation Performance

Composite structures containing silica in agar exhibited stronger capillary uptake relative to diatomite-rich formulations (Table 1). High-diatomite blends showed only minimal water-level decrease after several days at room temperature, whereas silica-dominant cylinders absorbed substantially more. Attaching a bacterial cellulose layer further accelerated uptake, increasing water absorption by over 50% during a 4.5-hour trial compared to silica-only structures, suggesting the role of bacterial cellulose as an effective wick that distributes moisture evenly across the interface. Condensation efficiency was also enhanced by the integration of bacterial cellulose. Using a simple plastic-cup lid condenser, the composite produced 0.62 g of condensate after 3 hours and 0.94 g after 24 hours, which was 1.7–2.0 times greater than the control (0.36 g and 0.43 g, respectively). Salinity tests confirmed that the recovered water had 0% salt content after 24 hours, indicating effective separation of salts during evaporation and condensation (Figure 2).

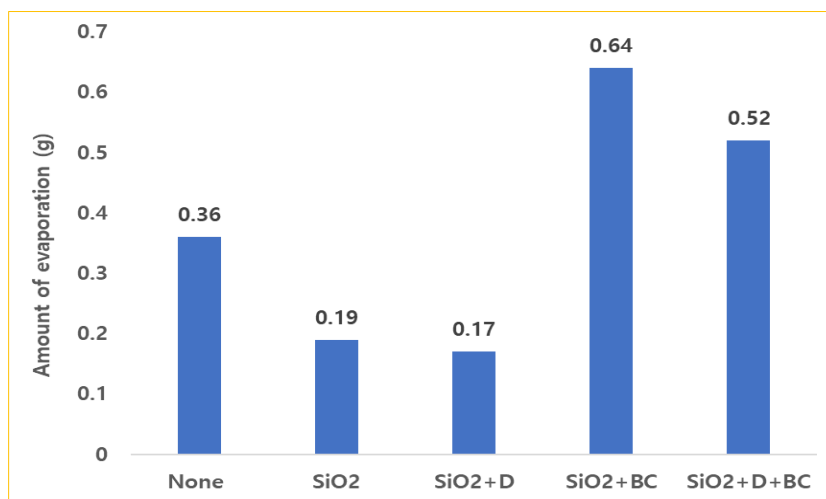


Figure 2. Amounts of water evaporated across four structural types and in the control.

3.2. Optimized Inverted BC-SiO₂-Fe Structure

Initial attempts to combine a parabolic cap with the cylindrical device suffered from interfacial cracking, which disrupted vapor movement and reduced efficiency. In response, the final design inverted the cylinder and treated the disk with iron oxide (Fe₃O₄) to localize heat at the air-water interface. This configuration also included a rigid base plate to stabilize the BC layer.

When operated under a lamp for 6 hours, this inverted BC-SiO₂-Fe device reduced source-water mass by approximately 13 g, of which 2.21 g was absorbed into the structure and 10.79 g was inferred as vaporized. Condensate collection yielded 0.84 g of water-14 times the volume condensed in the control setup (0.06 g; Figure 3). However, this corresponded to an overall condensation efficiency of only ~8%, highlighting the importance of mechanical sealing and condenser design in translating evaporation into usable water.

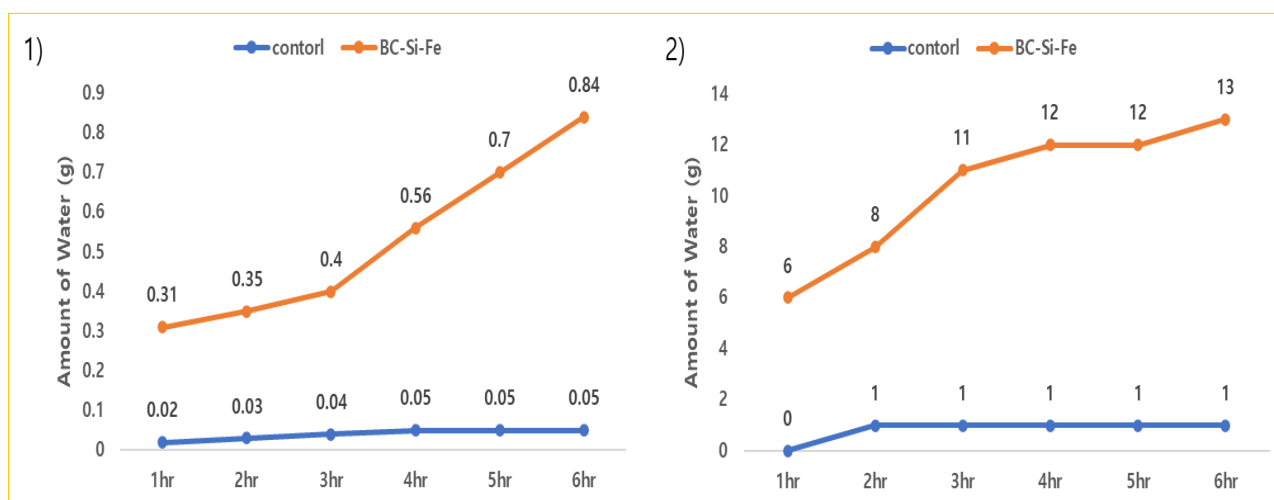


Figure 3. 1) Amount of water condensed on the lid after placement under a light bulb. 2) Amount of water in the control (SiO₂) and a composite with BC and SiO₂ and Fe₃O₄.

3.3. Material Substitutions: Fe_3O_4 Versus Biochar

A comparative set of experiments examined substitution of Fe_3O_4 with biochar, a low-cost porous carbon material. The Fe_3O_4 coating elevated surface temperatures by about $+10^\circ\text{C}$ relative to control during the first two hours of operation, providing localized photothermal heating (Figure 4). However, water-loss measurements indicated that evaporation rates were not consistently higher than control, suggesting that heating alone did not guarantee increased yield.

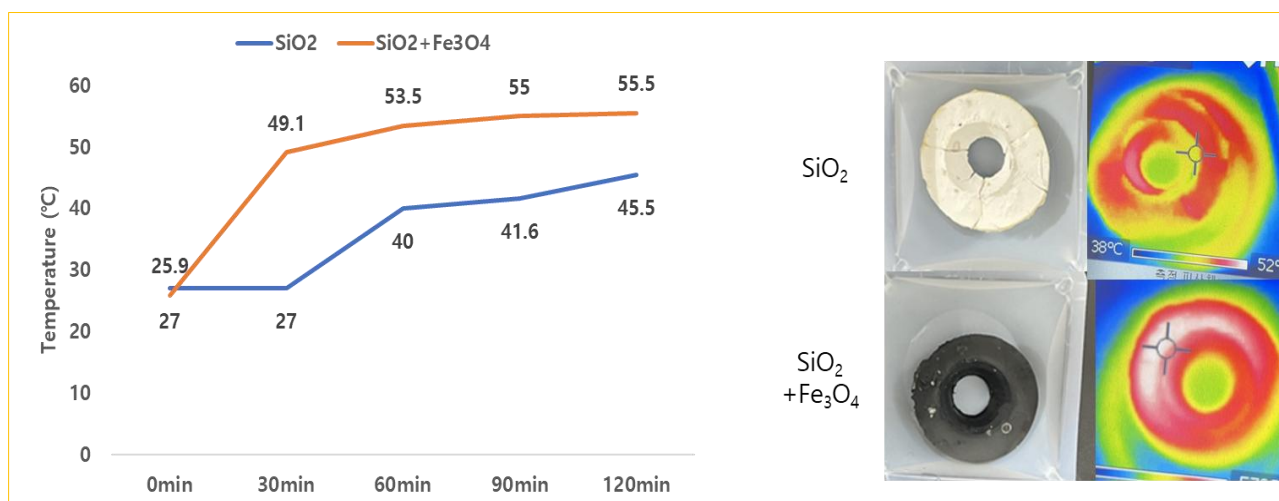


Figure 4. Temperature change and thermal distribution in the SiO_2 and $\text{SiO}_2 + \text{Fe}_3\text{O}_4$ parabolic structure after 120 min measured using an infrared camera.

Biochar substitution produced a different performance profile (Figure 5). The biochar- SiO_2 -BC composite absorbed 2.5 times its own weight in water, compared to 1.8 times in the non-biochar structure.

Over a 7-hour run, the structure with biochar exhibited a 30 percent mass reduction versus 16% in the silica-only control, indicating enhanced moisture removal. Yet, its surface temperature was $\sim 6^\circ\text{C}$ lower than the Fe_3O_4 case, reflecting biochar's capacity to store water while moderating photothermal heating. Together, these results suggest a trade-off: iron oxide Fe_3O_4 improves interfacial heating, while biochar improves absorption and water retention, with an integrated layered design likely offering the optimal performance.

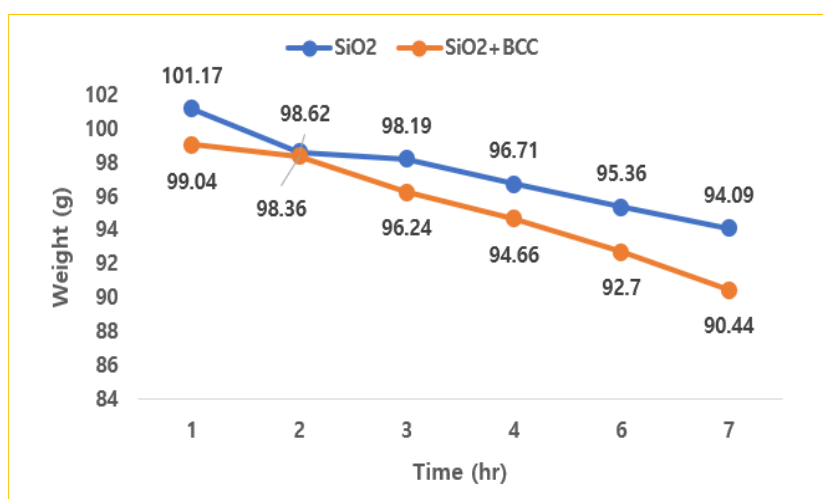


Figure 5. Mass change in water contained in SiO_2 and $\text{SiO}_2 + \text{biochar}$ structure.

3.4. Water Quality Assessment

To assess the potability of condensate, a brine shrimp hatchability assay was performed. Hatching rates were markedly lower in condensate water compared to the control, with an average of 0.2 larvae versus 2.0 larvae in control water. Dissolved oxygen measurements supported this finding, as condensate dissolved oxygen was only 1.1 ppm compared to 3.6 ppm in the control. While salt rejection was complete, the reduced oxygenation indicates that a simple post-aeration step may be necessary to ensure suitability for biological or human use.

3.4.1. Water Uptake, Evaporation, and Condensation Performance

Structures containing silica and diatomite in agar exhibited superior capillary uptake relative to diatomite-heavy formulations. High-diatomite samples (#3 and #4) showed only minimal water-level decrease after five days at room temperature, indicating diatomite-rich blends were less effective for rapid evaporation compared to SiO₂-rich mixes. A cylinder prepared with 10 g of silica and diatomite (SiO₂) in 100 mL of 1% agar showed stronger uptake than diatomite mixtures. Culturing and attaching bacterial cellulose on this composite further accelerated uptake, increasing water absorption by over 50 percent (50.38%) over 4.5 hours than in structures without bacterial cellulose.

Table 3. Key outcomes and design implications.

Experiment findings	Measured value	Design implications
BC-enhanced wicking	+50.38% absorption vs. SiO ₂ -only	Sustain feed to the interface
Fe ₃ O ₄ photothermal layer	≈+10 °C; 0.84 g/6 h condensate (14× control)	Thin heat-localizing skin; sealed paths
Biochar reservoir	Absorption ≈1.87×; surface −6 °C	Layer under BC to buffer supply
Evaporation vs. recovery	10.79 g evaporated/0.84 g condensed	Condenser efficiency dominates yield
Product water quality	0% salinity; DO 1.1 ppm	Add post-aeration step

3.5. Cost-Effectiveness Analysis Based on the Levelized Cost of Water Framework

The freshwater yield of the optimized inverted bacterial cellulose–silica–biochar configuration was first estimated using the most favorable laboratory measurements. Table 4 summarizes the assumptions and values used for Levelized Cost of Water (LCOW) modeling. Under controlled lamp heating, the structure achieved an evaporation rate of approximately 1.2 liters per hour, of which about 30 percent was recovered as condensate. Extrapolated to an operational schedule of eight hours per day across 300 days, this translates into a potential annual freshwater yield of approximately 0.864 m³. Applying a conservative capital cost of USD 1 per unit, a two-year device lifetime, and an annual operating expenditure of USD 0.20 (representing basic cleaning and membrane replacement), the LCOW was calculated at USD 0.85 per cubic meter. This figure compares favorably to the reported cost ranges of large seawater reverse osmosis plants (USD 0.50–1.50/m³), though the scale of production differs by several orders of magnitude.

Table 4. Assumptions and values used for levelized cost of water (LCOW) modeling.

Parameter	Assumptions / values	Notes
Capital expenditure (CAPEX)	1 USD per unit	Estimated cost of prototype fabrication using silica, agar, bacterial cellulose, biochar, and iron oxide coating.
Operating expenditure (OPEX)	i) Self-maintenance: negligible cost; ii) Outsourced maintenance: ~100 USD/year	Includes cleaning salt residues, replacing degraded components, and minor repairs. Outsourced cost benchmarked to gulf technician wages (820–1,600 USD/month depending on country).
Discount rate	5%	Weighted average cost of capital; consistent with gulf desalination cost studies.
Device lifetime	2 years	Conservative estimate; durability affected by bio-material degradation and structural stability.
Operating schedule	8 hours/day, 300 days/year	Assumes daylight operation under gulf solar conditions.
Condensation recovery	~0.84 g per 6 hours (~1.12 g per 8 hours)	Laboratory measurement under controlled illumination; recovery limited by condenser efficiency.
Annual freshwater yield	≈0.336 kg/year (≈0.000336 m ³ /year)	Based on extrapolated laboratory data.
Comparative benchmark	Reverse osmosis plants: 0.5–1.0 USD/m ³	Average cost range in the gulf region; included for contextual comparison.

However, when recovery is modeled using the average condensation performance recorded in the laboratory (0.84 g in six hours, or about 1.12 g/day scaled to Gulf solar conditions), the effective annual yield decreases sharply to approximately 0.000336 m³. Under this conservative scenario, the same capital and operational assumptions yield LCOW values that vary by orders of magnitude depending on maintenance

mode: an estimate of USD 1,600/m³ if the device is self-maintained, and up to USD 298,000/m³ if routine maintenance is outsourced to a household technician at regional wage levels. These extreme values underscore the sensitivity of small-scale desalination economics to condenser efficiency and recovered water volume (Table 5).

Table 5. Levelized cost of water (LCOW) scenarios.

Scenarios	Annual yield (m ³)	OPEX (USD/year)	LCOW (USD/m ³)
Base case (low yield, self-maintenance)	0.000336	0	1,607
Base case (low yield, technician maintenance)	0.000336	100	298,333
Optimal-performing structure (lab yield)	0.864	0.20	0.85
Optimal-performing (4-year lifetime, improved condenser)	0.864	0.20	0.42
Optimal-performing (self-maintenance, hot Gulf sunlight)	0.864+	0	<0.50 (projected)

The discrepancy between rapid absorption and modest evaporation rates observed during testing helps explain the divergence in yield estimates. Although the structure absorbed water quickly, the continuous supply of cold water to the surface prevented sufficient surface heating, thereby suppressing evaporation. In regions with high solar irradiance and ambient temperatures, such as the Gulf, this thermal limitation could be partially overcome as the natural solar input compensates for cooling effects, potentially narrowing the gap between absorption and evaporation efficiency.

Over a two-year lifetime, the base-case conservative scenario corresponds to ~0.000672 m³ of total freshwater recovered. The annualized capital expenditure was USD 0.54 (using a capital recovery factor of 0.538 at 5% discount rate), with operating expenditure set at either negligible levels (self-maintenance) or ~USD 100/year (outsourced maintenance). At this scale, LCOW is dominated not by capital cost but by the small denominator of recovered water. These results underscore both the limitations of current laboratory-scale configurations and the opportunity for significant cost reduction through materials optimization and design improvements.

Sensitivity analysis showed that extending device life to four years reduces the LCOW by approximately 50 percent (from ~22 USD/m³ to ~11 USD/m³ under the moderate-yield scenario), and further improvements in condenser efficiency could lower costs by an order of magnitude without additional capital investment. Enhancements such as expanding condensing area, engineering hydrophilic condensation surfaces, and improving vapor pathway sealing would yield significant gains. Similarly, material optimization-combining a thin iron oxide photothermal coating with bacterial cellulose wicking and a biochar reservoir-offers complementary pathways to improve both thermal efficiency and condensation yield.

4. Discussion

This study advances the field of solar-driven desalination by moving beyond theoretical assessments to the development and experimental validation of a prototype developed using layered structures made from accessible, low-cost materials from nature. The empirical results confirm that combining silica with agar enhanced water absorption, and that this effect was amplified when bacterial cellulose and biochar were included. When the surface was further coated with a thin layer of iron oxide, the structure demonstrated significant improvements in localized heating and vapor generation compared to silica alone. In principle, the most efficient configuration appeared to involve a layered arrangement where bacterial cellulose provided a capillary wick, biochar supplied a reservoir of absorbed water, and the iron oxide layer served as the principal heat-absorbing interface.

However, while these laboratory trials confirmed strong absorptive capacity, they also revealed a critical limitation. Because the composite structure absorbed water so effectively, it continually transported cool water to the surface. This constant supply produced a cooling effect, preventing the surface from heating up to the higher temperatures required for rapid evaporation. Infrared imaging confirmed that the surface remained relatively cool despite continuous illumination. Together, these features validated the central principle of interfacial solar evaporation-concentrating heat at the liquid-air interface while maintaining continuous hydration-while also diagnosing the practical bottlenecks of condensation efficiency and

structural stability. As such, the prototype could be refined to float at sea or deployed to facilitate the use of desalinized water for irrigation using a similar bottle-like device structure, as illustrated in Figure 6.

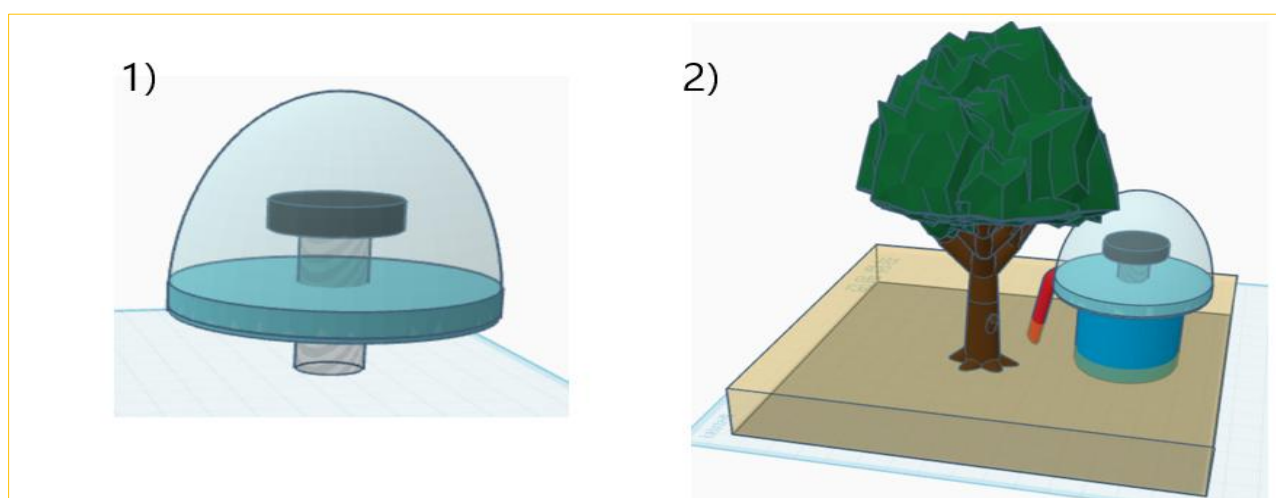


Figure 6. Conceptual drawing of the desalination plant based on a structure with the disk part treated by Fe_3O_4 and inverted, which exhibited the highest efficiency. 2) Conceptual drawing of a structure that facilitates irrigation of plants with desalinized water during drought as water moves through the red pipe.

Desalination is indispensable to the Gulf region's long-term water security, as natural groundwater reserves and surface water are insufficient to meet demand. Under Gulf climatic conditions, where solar radiation is intense and ambient temperatures are significantly higher, the cooling effect of continuous water supply would be less of a constraint. In such an environment, the background heat of the surface water combined with intense solar energy could allow the device to sustain evaporation more efficiently than in the laboratory setting. It is therefore reasonable to expect that the present laboratory results underestimate potential yields in the field, especially in hot and arid locations.

Current infrastructure is dominated by large thermal and reverse osmosis plants, which are costly to build, highly energy intensive, and environmentally problematic. The discharge of concentrated brine and chemicals into the semi-enclosed Gulf basin has been identified as a major ecological concern. The small-scale solar devices explored in this study address this environmental issue differently: by venting salt locally as crystalline deposits or through occasional low-concentration wash-off, they avoid the ecological risks associated with centralized brine disposal. Their reliance on natural sunlight rather than electricity further reduces the environmental footprint, offering a sustainable complement to existing large-scale infrastructure. Those outcomes collectively validate the central mechanistic premise of interfacial solar evaporation-localizing heat at the liquid-air boundary and feeding it with fast capillary supply-while translating it into a manufacturable form factor (Zhang *et al.*, 2021; Bai *et al.*, 2022).

4.1. Trade-Offs and Implications for Design

The experiments highlight several design trade-offs that require careful balancing. Biochar substantially increased water absorption and stability of evaporation but lowered the average surface temperature, reflecting the penalty of enhanced hydration. The iron oxide coating, on the other hand, improved surface heating and evaporation but lacked the storage capacity of biochar. High proportions of diatomite, though theoretically useful for increasing porosity, did not enhance evaporation and in fact appeared to limit effective water transport. These results indicate that material performance cannot be evaluated in isolation; it is the integration of different functions-capillary supply, heat localization, and vapor path management-that ultimately determines efficiency.

4.2. Cost-Effectiveness and Labor Considerations

Economic viability was evaluated using the levelized cost of water framework. In large municipal plants, costs typically range from 0.5 to 2.0 US dollars per cubic meter of freshwater, supported by economies of scale and long operating lifespans. Construction costs alone for a medium-sized reverse osmosis plant in the Middle East can exceed 50 million United States dollars. By contrast, the prototype presented here can be developed at a low cost, estimated at a dollar per unit, with no need for electricity or large-scale infrastructure. Operating costs depend heavily on labor cost assumptions. If users perform simple maintenance themselves-such as cleaning salt deposits and replacing degraded supports-the costs are

negligible. However, if such tasks were outsourced to household technicians, the economics would shift dramatically. Wages for technicians in the Gulf range from the equivalent of 820 to 950 United States dollars per month in the United Arab Emirates, approximately 1,370 United States dollars per month in Qatar, and around 1,600 United States dollars per month in Saudi Arabia (Herber, 2024). Allocating even a fraction of these wages to the maintenance of a single unit would dominate the economics of small-scale systems, making cost comparisons to conventional desalination plants inappropriate. While conventional, large-scale desalination plants deliver tens of thousands of cubic meters per day, the prototype currently produces only milliliters. In this context, the calculation of cost per cubic meter at laboratory scale is diagnostic rather than predictive. What matters is not the strict numerical comparison, but the accessibility and resilience offered by a device that requires virtually no capital investment, no external energy, and no complex inputs. Its true value lies in contexts where centralized desalination is unavailable, unreliable, or unaffordable, such as rural households, temporary camps, or disaster relief situations.

4.3. Pathways for Improvement and Scaling

The experiments revealed that condensation efficiency is the principal bottleneck. Laboratory trials showed that while over ten grams of vapor were generated in six hours, less than a gram was actually condensed and recovered. This imbalance underscores the need for improvements in condenser design, including increasing surface area, applying hydrophilic or dropwise coatings, ensuring effective drainage, and strengthening vapor seals. Enhancing structural stability, such as through rigid base plates and improved bonding, will also be necessary for field deployment.

Scaling can be achieved by tiling multiple small units together in modular arrays, thereby increasing throughput without increasing the thermal mass of individual devices. When combined with simple maintenance protocols, such as periodic rinsing and aeration, these refinements would not only raise yields but also improve water quality. Over time, such improvements could reduce the effective cost per cubic meter by an order of magnitude, even without altering the basic low-cost material palette.

Compared to prior research on water scarcity in the Gulf, which has focused primarily on documenting brine discharge and calling for alternative technologies, the findings of this study highlight the contrasting logics of scale in desalination. Large plants achieve low costs per cubic meter through scale, advanced energy recovery, and financing structures, but they require large initial investment capital, high operation and maintenance costs, and long-term institutional management, along with costs associated with environmental harm. Small interfacial solar desalination devices, by contrast, prioritize accessibility, decentralization, and environmental sustainability. While these small-scale devices cannot replace industrial-scale infrastructure to address global water supply, these innovations can complement conventional freshwater supply sources by providing emergency or supplementary water in settings where centralized supply is unavailable. In this sense, the study illustrates how material innovations, when coupled with careful design, can create new niches within the broader desalination landscape.

5. Conclusion

- ☞ This study presented a low-cost solar desalination prototype constructed from layered silica, agar, bacterial cellulose, and biochar, with an iron oxide surface treatment. Laboratory tests confirmed that the structure achieved rapid water absorption, measurable interfacial heating, and improved vapor generation compared to silica controls. The inverted configuration produced over ten grams of vapor in six hours, though recovery was limited by condenser inefficiency to less than one gram.
- ☞ These findings highlight both the promise and limitations of the approach. Material innovations validated the core principle of interfacial solar evaporation, but they also revealed the central importance of condenser design, sealing, and structural stability. Economic analysis reframed the high unit costs not as market estimates but as diagnostic indicators, clarifying which engineering refinements will most effectively reduce costs at small scales.
- ☞ The contribution of this study lies in linking material science with prototype fabrication, experimental validation, and cost analysis in a single framework. Unlike previous Gulf studies that emphasized problems without proposing implementable solutions, this research demonstrates a practical device that avoids brine discharge, requires no external energy, and can be fabricated for negligible capital cost. The prototype does not aim to replace industrial desalination but to complement it, providing decentralized, environmentally benign freshwater production for households, rural communities, or emergency settings.
- ☞ Future work should focus on field trials under Gulf sunlight, scaling condenser surfaces, reinforcing structural durability, and extending device lifetimes. With these improvements, small-scale solar

desalination could become a valuable component of regional water strategies, contributing to resilience, sustainability, and equitable access to freshwater.

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