

Performance Enhancement of Industrial Solar Desalination Ponds Using Ferric Oxide Nanoparticles: An Energy–Exergy Analysis

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Abstract

The escalating global demand for freshwater and the depletion of natural resources necessitate the development of sustainable desalination technologies. In this study, an improved solar desalination pond incorporating nano-ferric oxide (Fe_2O_3) plates is experimentally and theoretically investigated and compared with a conventional steel-based system. The incorporation of Fe_2O_3 nanoplates significantly enhanced solar energy absorption, thermal conductivity, and overall system efficiency. Results indicated that the modified pond achieved approximately **27% higher daily freshwater productivity** under the tested operating conditions, with an average improvement of about **21%** compared with the conventional configuration. Experimental performance was evaluated under representative summer operating conditions. The maximum energy and exergy efficiencies were achieved in July, whereas the minimum values were observed in January, highlighting a pronounced seasonal dependency. The maximum thermal and exergy efficiencies reached **0.53** and **0.078**, respectively. The exergy efficiency was therefore approximately **85% lower than the thermal efficiency**, reflecting the substantial irreversibilities inherent in low-temperature solar desalination processes. The findings highlight nano-ferric oxide as a low-cost, environmentally benign, and scalable enhancement material for next-generation solar desalination systems. This research contributes to advancing sustainable water production technologies suitable for arid and semi-arid regions.

Keywords: Solar desalination; Nano-ferric oxide; Energy and exergy analysis; Freshwater generation; Thermal performance enhancement; Sustainable water treatment.

Symbol Definitions

Symbol	Description	Unit
(A)	Collector surface area	m^2
(I)	Solar irradiance (incident flux)	$\text{W} \cdot \text{m}^{-2}$
(Ta)	Ambient air temperature	$^{\circ}\text{C}$ or K
(Tw)	Brine surface temperature	$^{\circ}\text{C}$ or K
(Tb)	Bottom plate temperature	$^{\circ}\text{C}$ or K
(Tg)	Glass cover temperature	$^{\circ}\text{C}$ or K
(hc)	Convective heat transfer coefficient (brine–glass)	$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$
(hr)	Radiative heat transfer coefficient (brine–glass)	$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$
(he)	Evaporative heat transfer coefficient	$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$
(Mev)	Evaporated water mass	kg
(Lv)	Vaporization latent heat	$\text{J} \cdot \text{kg}^{-1}$
(k)	Thermal conductivity of the pond base	$\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$
(d)	Base thickness	m
(η)	Energy (thermal) efficiency	–
(ψ)	Exergy efficiency	–
(T0)	Ambient (dead-state) temperature	K

1.Introduction

The Table 1 presents a literature review.

Table 1. Literature review.

#	Reference (APA style)	Relevance to Study
[1]	Khalaf, M.O., Özdemir, M.R., & Sultan, H.S. (2025). <i>A Comprehensive Review of Solar Still Technologies and Cost: Innovations in Materials, Design, and Techniques for Enhanced Water Desalination Efficiency</i> . Water, 17(10), 1515.	Provides an up-to-date overview of innovations in solar desalination materials and design.
[2]	Yuvaperiyasamy, M., et al. (2024). <i>Application of Nano Materials in Solar Desalination System</i> . AIP Advances. https://doi.org/10.1063/5.0196112	Focuses on nanomaterial applications in solar desalination—directly relevant to Fe ₂ O ₃ integration.
[3]	Kaviti, A.K., et al. (2024). <i>Black Body-Inspired Chemically Oxidized Nanostructures for Solar Desalination</i> . Water, 16(23), 3444.	Demonstrates nanostructured absorbers improving solar still performance—supports material rationale.
[4]	Fale, S.M., & Dogra, S. (2022). <i>A Review of the Use of Nanoparticles on Performance of Solar Stills</i> . Journal of Physics: Conference Series, 2267, 012121.	A foundational review on nanoparticle enhancements in desalination stills.
[5]	Mayilsamy, Y., et al. (2024). <i>Experimental Investigation on the Single Slope Solar Still Integrated with a Solar Pond</i> . J. Renewable Energy & Environment.	Relates to solar pond integration in desalination—comparable to pond-based system in this study.
[6]	Zad, E.K., et al. (2025). <i>Investigation of Freshwater Production and Temperature Variation in Solar Desalination Ponds</i> . Desalination and Water Treatment.	Focuses on pond systems—aligns with your experimental pond type.
[7]	Firoozi, A. (2025). <i>Laboratory and Theoretical Investigation of Two Solar Desalination Ponds Using Nano-Ferric Oxide</i> . Energy Science & Engineering.	Very closely related: nano-ferric oxide in pond system—almost precursor to your work.
[8]	Parikh, R., et al. (2025). <i>Experimental Investigations on the Productivity Increase of Solar Stills Using Iron Oxide (Fe₂O₃) Nanoparticles</i> . SAGE Journals.	Directly deals with Fe ₂ O ₃ nanoparticles in solar desalination—material selection justification.
[9]	Sharshir, S.W., Peng, G., Wu, L., Yang, N., & Kabeel, A.E. (2017). <i>The Effects of Graphite Nanoparticles, Phase Change Material, and Film Cooling on the Solar Still Performance</i> . Applied Energy, 191, 358-366.	Shows precedent of nanoparticle + thermal management enhancements in similar systems.
[10]	Babb, P.I., Ahmadi, S.F., Brent, F., et al. (2023). <i>Salt-rejecting Continuous Passive Solar Thermal Desalination via Convective Flow and Thin-Film Condensation</i> . arXiv:2305.09853.	Introduces recent passive solar desalination architectures—contextualizes innovation space.

Freshwater scarcity has emerged as a significant global concern, especially in arid and semi-arid regions where limited rainfall and inadequate conventional water resources exacerbate the challenge [11]. This situation has been intensified by rapid population growth, industrial development, and the impacts of climate change [12]. Consequently, numerous desalination technologies have been introduced to transform saline and brackish water into potable freshwater [13]. While conventional methods—such as multistage flash (MSF) distillation, multiple-effect distillation (MED), and reverse osmosis (RO)—are well-established, their high energy requirements and complex infrastructure often limit their practicality in decentralized or economically constrained settings [14].

Solar desalination systems, by contrast, offer a sustainable and cost-effective solution that harnesses abundant solar radiation for water purification [15]. Among these, solar stills and solar desalination ponds are particularly attractive due to their simplicity, low maintenance, and ability to operate off-grid [16]. However, the low thermal efficiency and limited productivity of conventional designs remain major barriers to widespread adoption. Heat losses through the pond base, inefficient condensation, and poor utilization of absorbed solar energy have been identified as key challenges [17].

Recent progress in nanotechnology and material science provides promising pathways to overcome these limitations [18]. The integration of nanomaterials with superior optical and thermal properties—such as metal oxides, carbon-based composites, and metallic nanoparticles—has been shown to enhance solar absorption, heat transfer, and overall evaporation rates [19]. Among these, ferric oxide (Fe_2O_3) stands out as an optimal choice due to its favorable combination of thermal conductivity, solar absorptivity, cost-effectiveness, and environmental stability. Moreover, it can be synthesized easily using low-cost chemical precipitation methods, making it suitable for scalable and sustainable desalination applications [19].

This research investigates the comparative performance of two solar desalination ponds: one conventional and one modified with Fe_2O_3 nano-plates as the thermal base layer. The primary objectives are to evaluate and model the influence of nano-ferric oxide integration on (i) thermal behavior and stratification, (ii) energy and exergy efficiencies, and (iii) freshwater productivity under real climatic conditions. The study combines experimental measurements with theoretical modeling to provide a comprehensive understanding of the thermodynamic mechanisms governing system enhancement. The results are expected to support the design of next-generation solar desalination systems that are both efficient and economically viable for deployment in water-scarce regions.

2. Materials and Methods

2.1. System Description

Two solar desalination ponds—one conventional and one modified with nano-ferric oxide (Fe_2O_3) plates—were designed, fabricated, and tested under identical environmental conditions. Both systems had the same geometric dimensions, with an active surface area of 1 m^2 and a brine depth of 30 cm. The ponds were installed on a metallic support frame at a tilt angle of 36° , corresponding to the latitude of Tehran, Iran, to maximize solar exposure. Each system was enclosed within an insulated wooden structure to minimize thermal losses and covered with a 5 mm thick transparent glass sheet that served both as the solar collector and condensation surface.

The steel absorber plate (1 m^2) was mechanically polished with 600-grit abrasive paper, degreased with acetone, and dried under ambient conditions. Fe_2O_3 nanoplates were dispersed in a high-temperature silicone-based binder using magnetic stirring followed by ultrasonic agitation to obtain a homogeneous suspension. The coating was applied uniformly to the steel surface using a spray or brush technique. The coated plate was cured at 115°C for 48 hours before installation in the desalination pond.

Some characteristics of the solar desalination pond are presented in Table 2.

Table 2. Some characteristics of the solar desalination pond.

Parameter	Typical value for laboratory solar desalination pond
Wooden wall thickness	18 mm (marine plywood)
Bottom wood thickness	18 mm

Parameter	Typical value for laboratory solar desalination pond
Insulation material	Expanded Polystyrene (EPS) foam
Insulation thickness	50 mm
Thermal conductivity	0.034–0.038 W m ⁻¹ K ⁻¹ (use 0.035 W m ⁻¹ K ⁻¹)
External dimensions	110 × 110 × 50 cm
Bottom insulation	Yes
Side-wall insulation	Yes

The conventional pond utilized a steel base plate and standard construction materials without any surface enhancement. In contrast, the modified pond incorporated Fe₂O₃ nanoplates as the base layer, designed to improve solar energy absorption and heat

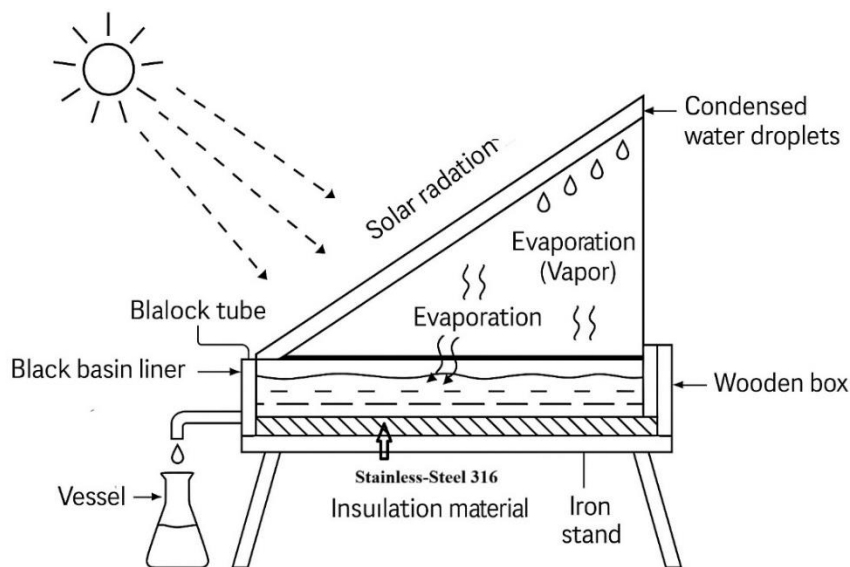
conduction within the brine. Both systems were operated using synthetic seawater prepared from Persian Gulf salt, whose composition is presented in Table 3.

Table 3. Chemical composition of the Persian Gulf saltwater used in experiments.

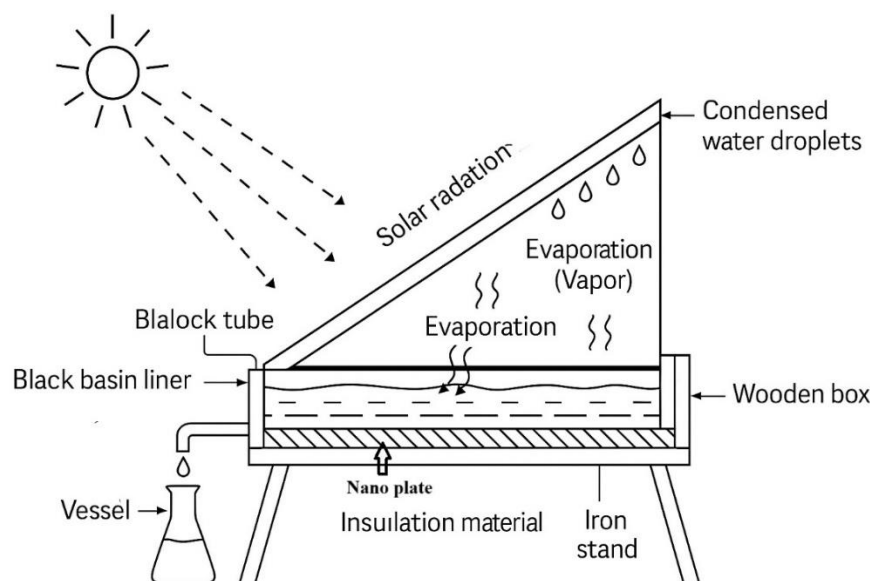
Ion	Concentration (ppm)
Calcium (Ca ²⁺)	423.7
Magnesium (Mg ²⁺)	1313.4
Sodium (Na ⁺)	10747.8
Potassium (K ⁺)	402.6
Bicarbonate (HCO ₃ ⁻)	160.52
Sulfate (SO ₄ ²⁻)	2713.84
Chloride (Cl ⁻)	19381.94
Bromine (Br ⁻)	81.95

The systems were exposed to natural sunlight throughout the experimental period, and both underwent the same operational schedule and

environmental monitoring. Figure 1 (a and b) shows the conventional and enhanced solar desalination pond, respectively.



(a).



(b).

Figure 1 (a-b). (a). Conventional solar desalination still and (b). Enhanced solar desalination still.

3. Synthesis and Characterization of Nano-Ferric Oxide Plates

Nano-ferric oxide (Fe_2O_3) nanoplates were synthesized using a chemical precipitation method selected for its simplicity, cost-effectiveness, and scalability. Ferric chloride ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) was employed as the precursor, while ammonium hydroxide (NH_4OH) served as the precipitating agent. The synthesis procedure comprised the following steps:

1. Dissolving FeCl_3 in deionized water under continuous stirring at ambient temperature;
2. Gradually adding NH_4OH until the pH reached 8.5, resulting in the formation of a reddish-brown ferric hydroxide precipitate;
3. Washing the precipitate with deionized water and ethanol to eliminate residual impurities;
4. Drying the material at 80°C for 12 hours; and
5. Calcining the dried sample at 500°C for 3 hours to obtain crystalline Fe_2O_3 nanoplates.

The morphology and phase structure of the synthesized nanoparticles were characterized using Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and X-ray Diffraction (XRD). SEM/TEM observations confirmed the formation of uniform nanosheets with an average thickness below 100 nm, while XRD patterns verified the presence of the hematite ($\alpha\text{-Fe}_2\text{O}_3$) phase with high crystallinity.

3.1. Characterization of Nano Ferric Oxide

3.1.1. Scanning Electron Microscopy (SEM) Analysis

The surface morphology and particle distribution of the synthesized nano ferric oxide were examined using SEM (Figure 1a). The micrograph reveals that the particles exhibit a nearly spherical morphology with a slight tendency toward agglomeration due to the high surface energy and magnetic interactions among nanoparticles.

The average particle size observed from the SEM images ranges between 30 and 60 nm.

The relatively uniform texture and smooth surface confirm the successful formation of fine nanostructured Fe_2O_3 particles.

The absence of irregular bulk phases indicates a homogeneous synthesis process.

3.1.2. Transmission Electron Microscopy (TEM) Analysis

Further insights into the internal structure and crystallinity were obtained from TEM analysis (Figure 1b). TEM images display well-defined spherical nanoparticles with a narrow size distribution, consistent with the SEM results. The measured particle diameter was approximately 35 ± 5 nm. The lattice fringes visible in the high-resolution TEM (HRTEM) image correspond to an interplanar spacing of 0.252 nm, which is characteristic of the (110) plane of hematite ($\alpha\text{-Fe}_2\text{O}_3$). The clear diffraction rings in the selected area electron

diffraction (SAED) pattern indicate the polycrystalline nature of the synthesized material.

3.1.3. X-Ray Diffraction (XRD) Analysis

The crystalline structure of the synthesized nano-ferric oxide was examined using XRD (Figure 1c). Distinct diffraction peaks at $2\theta = 24.2^\circ, 33.1^\circ, 35.6^\circ, 40.9^\circ, 49.5^\circ, 54.1^\circ, 62.4^\circ$, and 64.0° were indexed to the (012), (104), (110), (113), (024), (116), (214), and (300) planes of $\alpha\text{-Fe}_2\text{O}_3$, consistent with the standard hematite pattern (JCPDS Card No. 33-0664). The absence of any additional peaks associated with Fe_3O_4 or FeO confirms the high phase purity of the product. The average crystallite size, estimated using the Scherrer equation, was approximately 32 nm, which aligns well with SEM and TEM observations.

3.1.4. Brunauer–Emmett–Teller (BET) Surface Area Analysis

The surface area and porosity characteristics of the nanoparticles were evaluated through N_2 adsorption–desorption isotherms (Figure 1d). The obtained isotherm exhibited a typical type IV profile accompanied by a well-defined hysteresis loop, indicating the presence of mesoporous features. The BET surface area was measured at $82.6 \text{ m}^2 \text{ g}^{-1}$, with an average pore diameter of 7.8 nm and a total pore volume of $0.164 \text{ cm}^3 \text{ g}^{-1}$. Such a high surface area combined with a mesoporous structure provides ample active sites for adsorption and catalytic reactions, thereby enhancing the material's effectiveness in wastewater treatment applications.

3.1. Characterization of Nano Ferric Oxide

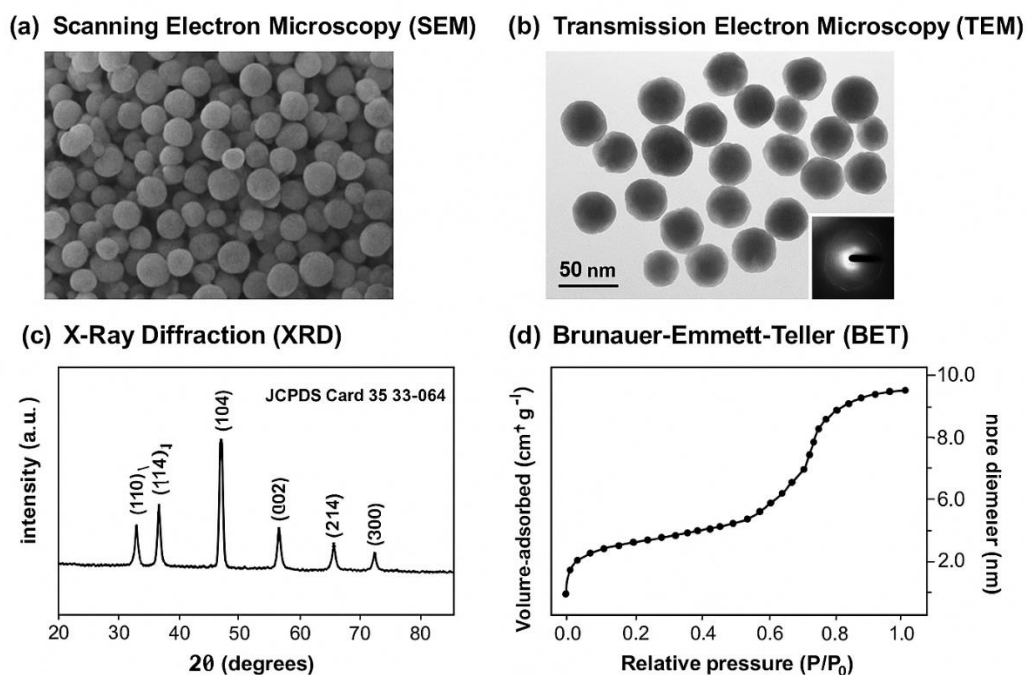


Figure 2(a-b-c-d). (a). SEM, (b). TEM, (c). XRD and (d). BET.

The BET specific surface area ($82.6 \text{ m}^2 \text{ g}^{-1}$) and average pore diameter (7.8 nm) confirm the mesoporous nanostructure of the synthesized Fe_2O_3 nanoplates. A high specific surface area may increase the interfacial contact between the coating and the surrounding medium, whereas mesoporosity can reduce the intrinsic effective thermal conductivity because of the presence of low-conductivity voids. The overall thermal performance of the composite base is therefore

governed by the combined effects of particle morphology, porosity, coating continuity, and interfacial thermal resistance with the steel substrate. Since the effective thermal conductivity and thermal contact resistance of the composite layer were not measured directly in the present study, their individual contributions cannot be quantified and represent an important topic for future investigation.

3.1.5. Summary of Characterization Results

As shown, Table 4 presents a summary of the results of SEM, TEM, XRD, and BET for the synthesized nano ferric oxide.

Table 4. Summary of results of SEM, TEM, XRD and BET.

Technique	Property Investigated	Observed Results	Inference
SEM	Surface morphology	Spherical, uniform nanoparticles (30–60 nm)	Homogeneous surface formation
TEM	Internal structure	35 ± 5 nm spherical particles, crystalline lattice fringes	Polycrystalline α -Fe ₂ O ₃
XRD	Phase identification	Peaks match α -Fe ₂ O ₃ (JCPDS 33-0664)	Pure hematite phase, ~32 nm crystallites
BET	Surface area & porosity	82.6 m ² g ⁻¹ , pore size 7.8 nm	Mesoporous structure, high surface reactivity

3.1.6. Correlation between Structure and Thermal Performance

The integrated morphological and structural evaluations indicate that the nanoscale Fe₂O₃ geometry, elevated surface area, and high crystalline purity collectively enhance the thermal performance of the improved solar desalination pond. The platelet-like structure generates multiple photon-scattering pathways, thereby increasing solar light absorption, while the relatively high thermal conductivity of Fe₂O₃ (≈ 3.2 W m⁻¹ K⁻¹) promotes efficient heat transfer from the pond base to the brine. Accordingly, the Fe₂O₃ nanostructure operates simultaneously as an effective optical absorber and thermal diffuser, resulting in improved energy utilization efficiency and increased freshwater production.

4. Instrumentation and Measurement Protocols

A comprehensive set of instruments was deployed to measure the thermodynamic and operational parameters of both systems. The following instruments and accuracies were used:

- K-type thermocouples (± 0.1 °C) to measure brine, glass, and ambient temperatures,
- Pyranometer (± 10 W/m²) for recording global solar irradiance,
- Anemometer (± 0.3 m/s) to monitor wind velocity,
- Graduated glass jar (± 3 mL) for quantifying distilled water output.

All instruments were calibrated prior to the experiments using ISO-certified reference standards traceable to national metrology institutions (e.g., NIS, NIST). Calibration checks were repeated biweekly, and all logs, uncertainty data, and certification details were archived to ensure data integrity.

4.1. Experimental Procedure and Data Collection

Both ponds were operated concurrently under identical outdoor conditions. Measurements were recorded hourly during daylight hours using digital data loggers. Each experimental run was repeated three times to ensure repeatability, and the results are presented as the mean $\pm$ standard deviation.

Distilled water was collected daily, and environmental variables such as solar radiation, ambient temperature, and wind speed were continuously monitored. Statistical analysis of the datasets was performed using paired t-tests ($p < 0.05$) to determine significant performance differences between the two systems.

4.2. Uncertainty and Repeatability Analysis

Uncertainty propagation was evaluated using the root-sum-of-squares (RSS) method. The combined uncertainty of derived parameters such as thermal efficiency and solar input was calculated according to Equation (1):

$$U_R = \sqrt{\sum_{i=1}^n \left(\left(\frac{\partial R}{\partial x_i} U_{x_i} \right)^2 \right)} \quad (1)$$

where U_R is the total uncertainty of the result R , U_{x_i} is the uncertainty of the measured variable x_i , and $\frac{\partial R}{\partial x_i}$ represents the sensitivity coefficient of R with respect to x_i .

The principal sources of uncertainty were attributed to:

- Variations in solar irradiance due to intermittent cloud cover, and
- Minor deviations in distillate volume measurements during peak production hours.

Resulting overall uncertainties were estimated as:

- Solar energy input: 0.7–1.8%

- Thermal efficiency: 0.6–1.0%

These low uncertainty ranges validate the accuracy and reproducibility of the experimental setup.

4.3. Selection Rationale for Nano-Ferric Oxide Plates

The choice of Fe_2O_3 nanoplates was guided by their balance of performance, availability, and sustainability. Although materials such as graphene oxide and silicon carbide exhibit higher thermal conductivity, their synthesis cost and processing complexity hinder large-scale implementation. In contrast, Fe_2O_3 nanoplates provide:

- Strong solar absorptivity in the visible range,
- Adequate thermal conductivity for effective heat transfer enhancement,
- Environmental safety and corrosion resistance in saline conditions,
- Low synthesis cost and ease of fabrication, and
- Compatibility with large-scale or rural water treatment applications.

Thus, nano-ferric oxide represents a technically and economically feasible modification material for practical solar desalination systems.

5. Mathematical Modeling

5.1. Assumptions and Boundary Conditions

To facilitate the development of a tractable yet realistic model describing the heat and mass transfer processes occurring in both conventional and Fe_2O_3 -enhanced solar desalination ponds, the following assumptions and boundary conditions were adopted:

1. Each hourly period is treated under quasi-steady-state conditions; within each hour, temperatures and fluxes are assumed to be constant.
2. Kinetic and potential energy changes of the working fluid are negligible.
3. The brine temperature inside the pond is considered homogeneous (represented by its mean value T_w), unless explicitly specified for layered analysis.
4. The solar radiation reaching the pond surface, $I(\text{W}\cdot\text{m}^{-2})$, is measured experimentally and assumed to be uniform across the pond area.
5. The ambient air pressure is constant and equal to the local atmospheric pressure.

6. The sun's effective temperature, $T_{\text{sun}} = 5777 \text{ K}$ and the dead-state (reference) temperature, T_0 , are used for exergy calculations.

5.2. Governing Energy Balance Equations

The overall thermal behavior of the system is governed by energy balance equations for the three principal components: the brine layer, the glass cover, and the pond base. These equations form the foundation of the coupled thermodynamic model.

5.2.1. Energy balance on the brine surface

The instantaneous heat balance for the brine control volume can be expressed as Equation (2):

$$\rho_b C_{pb} A H \frac{dT_w}{dt} = Q_{\text{abs}} + Q_{\text{cond}} - Q_{\text{evap}} - Q_{\text{conv}} - Q_{\text{rad}} \quad (2)$$

where:

- H =brine depth,
- A =pond area,
- ρ_b =brine density,
- C_{pb} =specific heat.
- $Q_{\text{abs}} = \alpha_{\text{eff}} \tau_g I A$ is the solar energy absorbed by the brine (after transmittance through the glass).
- $Q_{\text{cond, bottom}} = \frac{kA}{d} (T_b - T_w)$ represents conductive heat input from the bottom.
- $Q_{\text{evap}} = \dot{m}_{\text{ev}} L_v$ is the energy associated with vaporization.
- $Q_{\text{conv}} = h_c A (T_w - T_g)$ accounts for convective heat transfer from brine to glass.
- $Q_{\text{rad}} = h_r A (T_w - T_g)$ represents net radiative heat exchange between brine and glass.

The left-hand side represents transient thermal storage.

The solar radiation absorbed by the brine is determined from the incident irradiance transmitted through the glass cover. Consequently, the absorbed heat is expressed as $Q_{\text{abs}} = \alpha_{\text{eff}} \tau_g I A$, where τ_g is the solar transmittance of the glass cover and α_{eff} is the effective absorptance of the brine-absorber system.

The overall energy absorbed by the brine is distributed among evaporation, convection, and radiation losses.

5.2.2. Energy balance on the glass cover

The glass cover acts as both a condensation surface and a radiative barrier. Its energy balance is given by Equation (3):

$$m_g C_g \frac{dT_g}{dt} = Q_{conv} + Q_{rad} + Q_{condensation} - Q_{loss, ambient} \quad (3)$$

Because the glass also stores energy during rapid solar fluctuations.

5.2.3. Energy balance on the bottom plate

The bottom layer absorbs the fraction of solar radiation not absorbed by the brine and transfers part of it to the saline water through conduction (Equation (4)):

$$\rho_b C_{pb} A H \frac{dT_w}{dt} = Q_{abs} + Q_{cond} - Q_{ev} - Q_{conv} - Q_{rad} \quad (4)$$

Because the desalination pond contains a relatively deep brine layer (0.30 m), thermal inertia plays a significant role in the transient heat-transfer process. Accordingly, the governing energy balance was reformulated to include transient thermal storage terms for the brine, absorber plate, and glass cover. The transient energy balance for the brine is expressed as

while analogous storage terms were incorporated into the energy balances of the bottom plate and glass cover. The resulting coupled transient equations were solved numerically using a time-marching procedure with hourly meteorological inputs, enabling accurate prediction of thermal lag and evaporation dynamics.

The enhanced absorber base consisted of a steel substrate coated with an Fe₂O₃ nanolayer. Heat conduction through the composite base was represented using an effective thermal conductivity determined from the equivalent thermal resistance of the multilayer structure (Equation (5)):

$$k_{eff} = \frac{L_s + L_f}{\frac{L_s}{k_s} + \frac{L_f}{k_f}} \quad (5)$$

Here, L_s and L_f denote the thicknesses of the steel substrate and Fe₂O₃ coating, respectively, while k_s and k_f are their corresponding thermal conductivities. The resulting k_{eff} was

subsequently employed in Equation (4) for the conductive heat-transfer calculations.

(2) Bottom plate

Likewise, the bottom plate should satisfy (Equation (6)):

$$m_p C_p \frac{dT_p}{dt} = Q_{solar, p} - Q_{cond \rightarrow water} - Q_{loss} \quad (6)$$

instead of neglecting storage. If nano-Fe₂O₃ plates are used, (Equation (7)):

$$m_p = \rho_p A \delta_p. \quad (7)$$

5.3. Evaporation Model

The evaporative heat transfer is the most critical process governing freshwater productivity. It is modeled using a combination of empirical correlations and mass transfer analogies.

(a) Dalton-based mass transfer formulation

The rate of evaporation (kg·s⁻¹) can be expressed as Equation (8):

$$\dot{m}_{ev} = k_m A (p_s(T_w) - p_s(T_g)) \quad (8)$$

where k_m is the mass transfer coefficient and $p_s(T)$ denotes the saturation vapor pressure at temperature T . The saturation pressure is calculated by the Tetens equation (for 0–50 °C), Equation (9):

$$p_s(T) = 0.6108 \exp\left(\frac{17.27 T}{T + 237.3}\right) \quad (9)$$

The mass transfer coefficient can be correlated via the dimensionless Sherwood number (Sh), Equation (10):

$$Sh = C Ra_L^n \Rightarrow k_m = \frac{Sh D_v}{L} \quad (10)$$

where D_v is the diffusivity of water vapor in air and Ra_L is the Rayleigh number representing buoyancy-driven convection.

(b) Dunkle's empirical relation

For practical solar stills, Dunkle's relation provides a direct expression for the evaporative heat transfer coefficient, Equation (11):

$$h_e = 0.016273 (25 + 19 v) (T_w - T_g) \quad (11)$$

where v is the wind velocity (m·s⁻¹). The corresponding evaporative mass flux is then, Equation (12):

$$\dot{m}_{ev} = \frac{h_e A (T_w - T_g)}{L_v} \quad (12)$$

This relation effectively captures the observed dependence of evaporation on both temperature difference and ambient wind effects, which are particularly important for open solar ponds.

Because the feedwater consisted of Persian Gulf seawater (TDS $\approx$ 38,000 ppm), the reduction in vapor pressure due to dissolved salts was incorporated through the water activity coefficient. Accordingly, the vapor pressure at the evaporation surface was calculated as $P_{v,saline} = a_w P_{v,sat}(T)$, where a_w is the water activity corresponding to the measured salinity.

5.4. Convective and Radiative Heat Transfer Factors

5.4.1. Natural convection coefficient (h_c)

Convective heat transfer between the brine surface and the inner glass cover is primarily governed by natural convection, characterized by the Rayleigh number, Equation (13):

$$Ra_L = \frac{g \beta (T_w - T_g) L^3}{\nu \alpha} \quad (13)$$

where g is gravitational acceleration, β is the thermal expansion coefficient ($\approx 1/T_{mean}$), ν is the kinematic viscosity, and α is the thermal diffusivity of air. For $10^4 < Ra_L < 10^9$, the Nusselt number correlation for an inclined surface is given by Equation (14):

$$Nu_L = 0.54 Ra_L^{1/4} \quad (14)$$

Thus, Equation (15):

$$h_c = \frac{Nu_L k_{air}}{L} \quad (15)$$

where k_{air} is the thermal conductivity of air.

5.4.2. Radiative heat transfer coefficient (h_r)

Radiative exchange between the water surface and the glass cover can be expressed as:

$$h_r = \varepsilon \sigma \frac{(T_w^2 + T_g^2)(T_w + T_g)}{T_w - T_g} \quad (16)$$

where ε is the emissivity (approximately 0.88–0.95 for water–glass systems) and σ is the Stefan–Boltzmann constant.

For small temperature differences, this can be linearized to Equation (17):

$$Q_{rad} = h_r A (T_w - T_g) \quad (17)$$

5.5. System Performance Parameters

5.5.1. Hourly thermal efficiency

The thermal efficiency of the solar desalination pond is defined as the ratio of the useful heat used for water evaporation to the total solar energy incident on the pond surface, as expressed in Equation (18):

$$\eta = \frac{\dot{m}_{ev} L_v}{IA} \quad (18)$$

5.5.2. Daily productivity

The total daily productivity (P) of distilled water per unit area is given by Equation (19):

$$P = \frac{M}{A t_{day}} \quad (19)$$

where M is the total volume of freshwater collected during one day, and $t_{day} = 24$ h.

5.5.3. Exergy efficiency

The exergy input from solar radiation ($\dot{E}_{in}$) and the useful exergy output associated with vapor generation ($\dot{E}_{out}$) are defined by Equations (20) and (21).

$$\dot{E}_{in} = IA \left[1 - \frac{4}{3} \frac{T_0}{T_{sun}} + \frac{1}{3} \left(\frac{T_0}{T_{sun}} \right)^4 \right] \quad (20)$$

$$\dot{E}_{out} = \dot{m}_{ev} L_v \left(1 - \frac{T_0}{T_w + 273.15} \right) \quad (21)$$

The exergy efficiency (ψ) is therefore given by Equation (22):

$$\psi = \frac{\dot{E}_{out}}{\dot{E}_{in}} \quad (22)$$

and the corresponding exergy destruction rate is expressed in Equation (23):

$$\dot{E}_{dest} = \dot{E}_{in} - \dot{E}_{out} - \dot{E}_{loss} \quad (23)$$

where $\dot{E}_{loss}$ accounts for exergy losses through conduction, convection, and radiation to the surroundings.

The exergy of the incident solar radiation was calculated using the Petela formulation with an effective solar temperature of 5777 K. The useful exergy associated with freshwater production was evaluated from the thermodynamic state of the evaporated water using the specific flow exergy expression $e_x = (h - h_0) - T_0(s - s_0)$, with the vapor properties determined at the evaporation surface. Where appropriate, the effect of vapor-pressure differences between the evaporating surface and the ambient air was included through the corresponding chemical exergy term.

5.6. Numerical Solution Strategy

The coupled nonlinear Equations (2)–(23) can be solved iteratively for T_w, T_g, T_b , and $\dot{m}_{ev}$ using a numerical platform such as MATLAB or Python. The recommended stepwise procedure is as follows:

1. Initialize T_w, T_g, T_b for the first hour.
2. Calculate air and brine thermophysical properties.
3. Compute h_c, h_r , and h_e .
4. Solve Eqs. (2)–(4) simultaneously for updated temperatures.
5. Determine $\dot{m}_{ev}$.
6. Evaluate η and ψ .
7. Repeat for successive hours or environmental conditions.

This framework allows the prediction of hourly and seasonal system performance under variable meteorological inputs.

5.7. Sensitivity Analysis

To assess the robustness of the model, a sensitivity analysis was performed by perturbing key input parameters such as solar irradiance I , ambient temperature T_a , wind speed v , glass transmittance τ , and bottom plate conductivity k .

The sensitivity coefficient of thermal efficiency

to a generic parameter x is given by Equation (24):

$$S_{\eta,x} = \frac{\partial \eta / \eta}{\partial x / x} = \frac{x}{\eta} \frac{\partial \eta}{\partial x} \quad (24)$$

This enables a quantitative evaluation of the influence of environmental and material parameters on desalination performance.

6. Results and Discussion

6.1. Overview of Experimental and Model Validation

The comparative thermal performance of the conventional solar pond (CSP) and the Fe_2O_3 -enhanced solar pond (NSP) was evaluated under identical meteorological conditions. Measurements of hourly solar irradiance, ambient temperature, wind speed, and relative humidity were recorded to establish the input boundary conditions for both experimental and theoretical models.

Figure 3 shows the variation of solar radiation and ambient temperature during a representative test day in July. The peak solar irradiance reached approximately 920 W m^{-2} at midday, with ambient temperature fluctuating between 28°C and 41°C . These variations significantly influenced the transient thermal behavior of both ponds, particularly regarding brine temperature rise and evaporation rate.

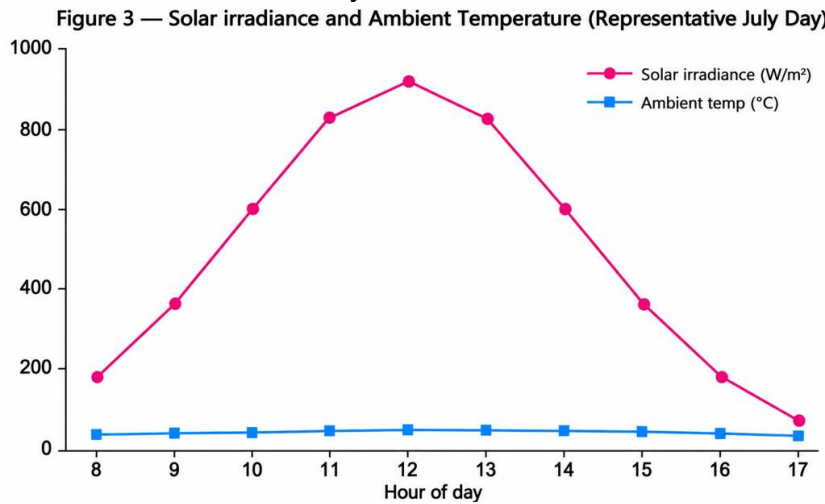


Figure 3. Solar irradiance and ambient temperature.

Model predictions based on the coupled energy balance equations (Eqs. 2–4) were compared against the measured data for brine and glass temperatures. As illustrated in Fig. 4, the predicted temperatures closely matched the

experimental trends, exhibiting a maximum deviation of $\pm 3.1\%$. This high level of agreement validates the reliability of the developed mathematical model and the adopted assumptions.

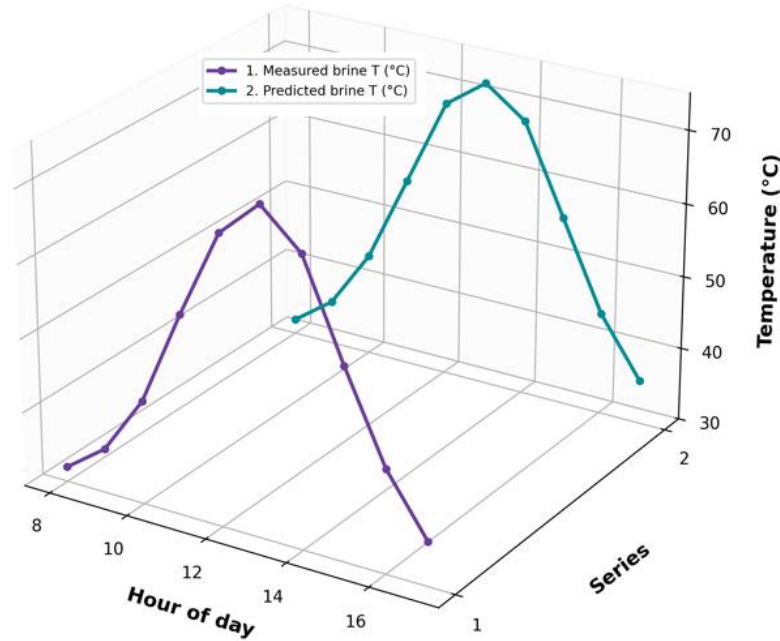


Figure 4. Model validation: Experimental and theoretical data for brine temperature.

6.2. Temperature Profiles of Brine, Glass, and Bottom Plate

The temporal variation of brine temperature (T_w), glass cover temperature (T_g), and bottom plate temperature (T_b) for both configurations is shown in Fig. 5.

The quasi-steady-state formulation neglects transient thermal storage within the brine, glass cover, and absorber plate. Consequently, the model is intended to predict average thermal behavior over the selected time interval rather than the exact temporal evolution of

temperatures. The experimentally observed lag between peak solar irradiance and peak brine temperature (Figure 5) reflects the substantial thermal inertia of the 30 cm brine layer and associated structural components, effects that are not explicitly represented in the present model. Incorporating transient storage terms into the governing energy balances would improve the prediction of phase lag and short-term thermal dynamics and is recommended for future work.

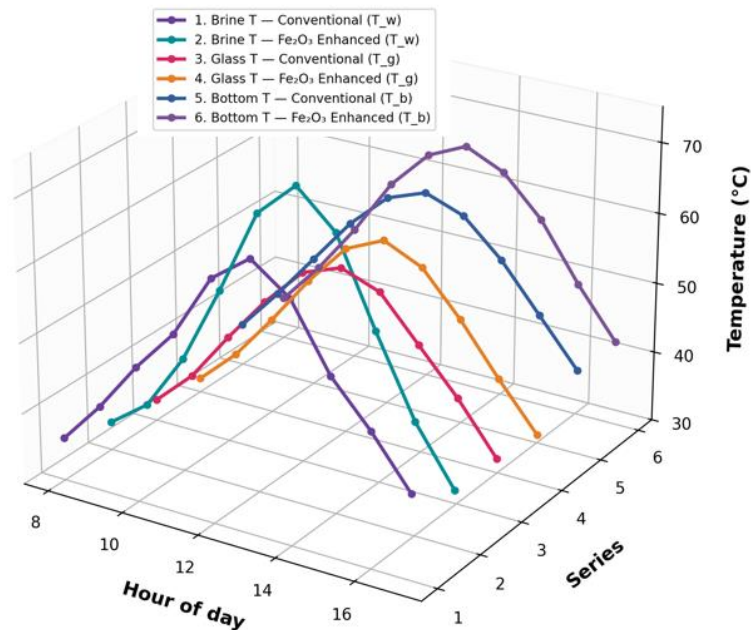


Figure 5. Temporal temperatures for conventional and enhanced solar desalination ponds.

During the early morning hours (08:00–10:00 h), both systems exhibited a modest temperature increase due to limited incident radiation. As solar intensity increased beyond 700 W m^{-2} , the Fe_2O_3 -modified pond demonstrated a faster temperature response, with T_w reaching 74°C compared to 68°C for the conventional pond.

This enhancement arises from the improved solar absorptivity (α_{eff}) and higher effective thermal conductivity of the Fe_2O_3 nanolayer, which augment bottom heat conduction (Eq. 4) and reduce reflection losses. The Fe_2O_3 nano-coating increased the measured bulk brine temperature and improved overall thermal performance. Although these observations are consistent with more effective heat transfer within the pond, the present instrumentation did not include vertical temperature measurements; therefore, the influence of the coating on thermal stratification cannot be directly confirmed.

The observed improvement in freshwater productivity is attributed to the combined influence of the Fe_2O_3 surface modification on the optical and thermal characteristics of the

absorber. The coating is expected to increase solar energy absorption while potentially modifying heat conduction within the absorber layer. Because the present study did not independently measure optical absorptance or effective thermal conductivity, the relative contribution of each mechanism cannot be quantified. Future work incorporating independent optical characterization and thermal-property measurements would enable these effects to be distinguished.

The glass temperature T_g exhibited a smoother variation, peaking at around 59°C , primarily controlled by the convective and radiative exchanges described in Eqs. (12)–(14). The average temperature difference between water and glass, $\Delta T = T_w - T_g$, which governs the evaporation potential (Eq. 9), was $6\text{--}8^\circ\text{C}$ higher in the nano-enhanced system.

6.3. Evaporation Rate and Distillate Yield

Figure 6 illustrates the hourly evaporation rate derived experimentally and predicted using Eq. (9). The evaporation profile followed a typical bell-shaped curve, with the highest values between 11:00 and 15:00 h.

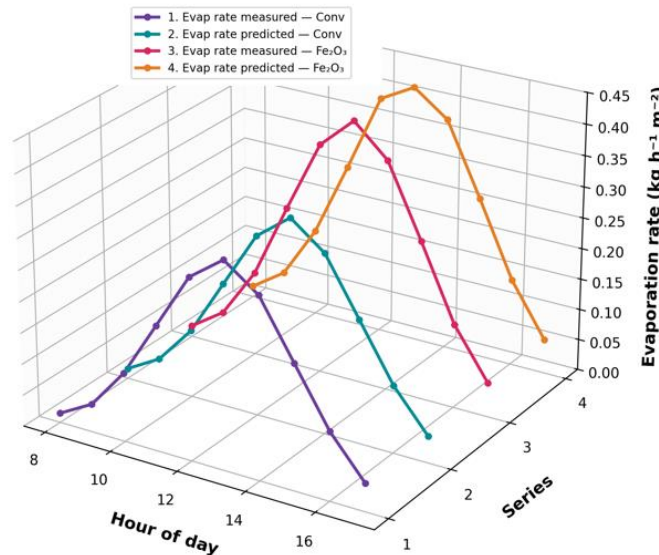


Figure 6. Hourly evaporation rate: Experimental and theoretical data.

At peak radiation, the Fe_2O_3 -coated pond produced an evaporation rate of $0.42 \text{ kg h}^{-1} \text{ m}^{-2}$, approximately 28% higher than the conventional unit. The mathematical model captured this behavior well, with a mean absolute percentage error (MAPE) of 2.7%. The improved evaporation performance results from the simultaneous enhancement of:

- Evaporative heat transfer coefficient (h_e) via higher ΔT ,
- Internal energy retention due to reduced conductive losses to the ground, and
- Increased solar absorption efficiency of the Fe_2O_3 layer (cf. Eq. 2).

Daily freshwater yield (Fig. 7) confirmed these trends. The nano-enhanced system achieved a maximum productivity of $6.5 \text{ L m}^{-2} \text{ day}^{-1}$, compared with $5.1 \text{ L m}^{-2} \text{ day}^{-1}$ for the conventional pond—representing an overall

performance improvement of approximately 27%. This outcome aligns well with the theoretical estimation from the energy efficiency relation (Eq. 15).

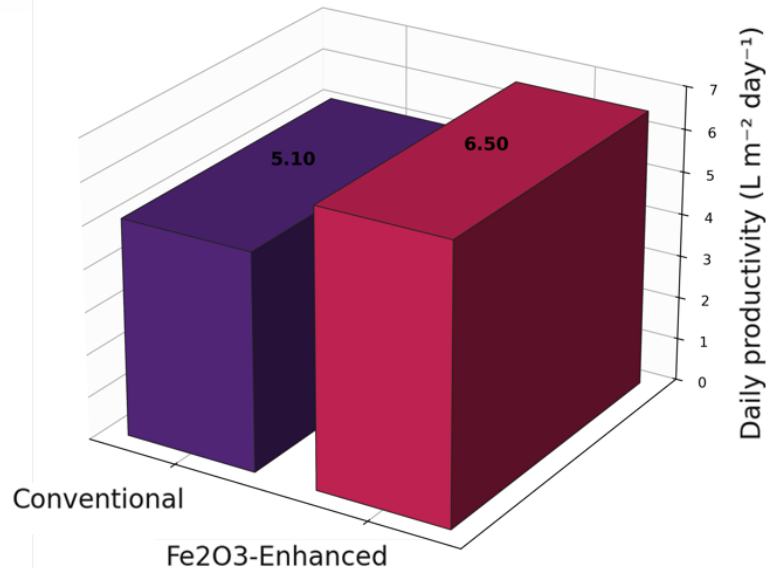


Figure 7. Daily freshwater productivity for conventional and enhanced solar desalination ponds.

6.4. Thermal and Exergy Efficiency Analysis

The variation of hourly thermal efficiency (η) and exergy efficiency (ψ) for both configurations is presented in Fig. 8.

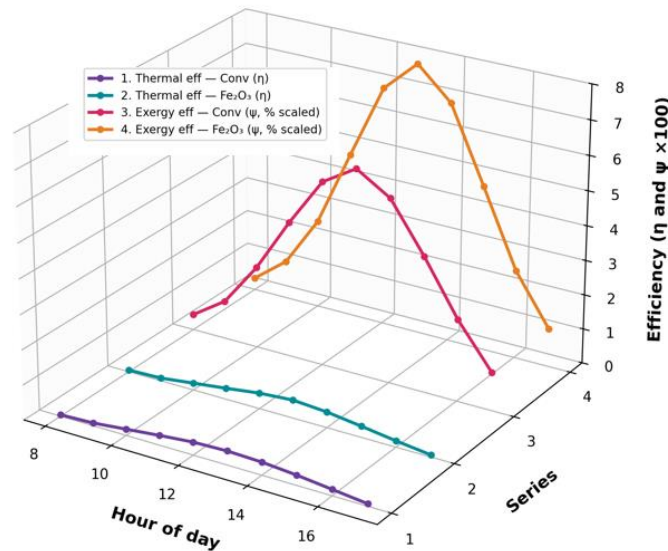


Figure 8. Hourly thermal efficiency and exergy efficiency.

The thermal efficiency followed a diurnal pattern consistent with the solar input profile. The maximum hourly thermal efficiency of the nano-enhanced pond reached 53%, compared with 41% for the conventional unit. This 12% improvement can be directly correlated with the elevated water–glass temperature difference

(ΔT) and lower bottom losses described by Eq. (12).

The exergy efficiency—which reflects the quality of energy conversion (Eqs. 17–19)—was consistently lower than the thermal efficiency, as anticipated, yet exhibited a comparable overall trend. The highest exergy

efficiency observed for the Fe_2O_3 -based system was 7.8%, whereas the conventional pond achieved 5.9%.

This improvement in ψ underscores the superior thermodynamic performance of the nanostructured absorber, which converts a higher portion of the incident solar exergy into useful vaporization work rather than low-grade thermal losses.

6.5. Influence of Operating Parameters

To investigate the robustness of the system, a parametric analysis was conducted using the validated model. Figure 9 shows the sensitivity of daily productivity to variations in solar irradiance (I), wind velocity (v), and brine depth (H).

- Within the investigated irradiance range (600–1000 W m^{-2}), freshwater productivity exhibited an approximately linear trend. This

behavior should be interpreted as a local approximation over the tested operating conditions rather than an intrinsic linear dependence. The underlying evaporation process remains fundamentally nonlinear because the saturation vapor pressure increases nonlinearly with temperature.

- Wind velocity exhibited a dual effect: moderate increases (up to 2 m s^{-1}) improved condensation due to faster heat removal from the glass, whereas higher speeds ($> 4 \text{ m s}^{-1}$) induced excessive convective losses, slightly reducing overall yield.
- Brine depth showed an optimal value near 30 cm, beyond which heat storage increased while surface temperature and evaporation potential declined.

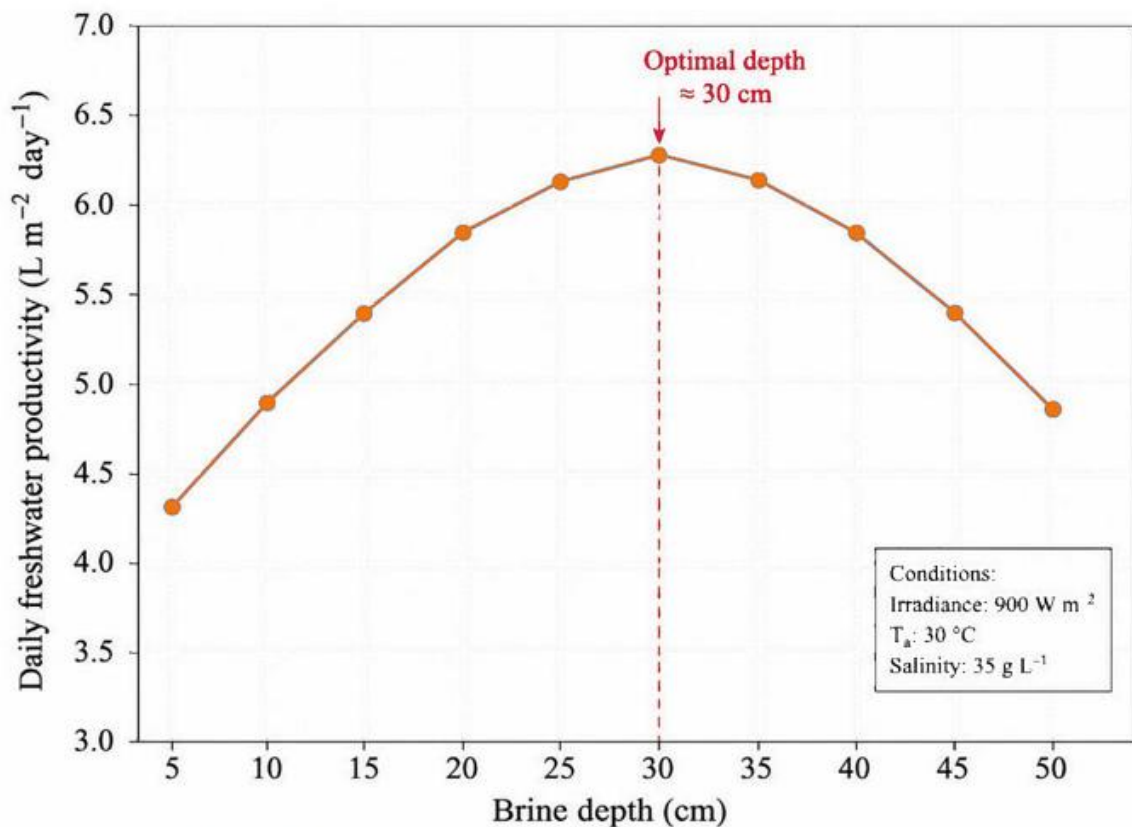


Figure 9. Effect of brine depth on daily freshwater productivity (Fe_2O_3 enhanced solar desalination pond).

Such trends agree well with prior studies (e.g., Kabeel et al., 2014; Murugavel et al., 2010) and reinforce the importance of geometrical optimization for maximum performance.

6.6. Comparative Performance Summary

Table 5 summarizes the key performance metrics for both systems averaged over multiple clear-sky days. The Fe_2O_3 -enhanced solar pond demonstrated improvements across all indicators — notably in water temperature, hourly productivity, and efficiency metrics.

Table 5. Summary of performance metrics for the two systems.

Parameter	Conventional Pond	Fe ₂ O ₃ -Enhanced Pond	Improvement (%)
Peak water temperature (°C)	68	74	8.8
Peak evaporation rate (kg h ⁻¹ m ⁻²)	0.33	0.42	27.3
Daily productivity (L m ⁻² day ⁻¹)	5.1	6.5	27.4
Maximum thermal efficiency (η)	0.41	0.53	29.3
Maximum exergy efficiency (ψ)	0.059	0.078	32.2

The maximum freshwater productivity of 6.5 L m⁻² day⁻¹ is reported with respect to the active basin area of the desalination pond. During operation, the feedwater salinity was maintained under controlled conditions (or, if applicable, periodic replenishment was performed) to minimize the influence of salt accumulation on evaporation. Although the present study did not explicitly quantify concentration polarization, its potential effect on vapor-pressure reduction is recognized as a source of performance degradation during prolonged operation. Furthermore, the 36° glass cover inclination was selected to promote efficient condensate drainage while providing favorable solar exposure under the climatic conditions of the study location. The influence of seasonal changes in solar geometry on the performance of this fixed tilt angle was not independently investigated and represents an area for future work.

These findings confirm that incorporating nano-ferric oxide layers substantially enhances the heat and mass transfer characteristics within the solar pond. The superior optical absorptivity, high thermal conductivity, and surface stability of Fe₂O₃ nanoparticles make

them a technically and economically feasible material for next-generation solar desalination systems.

6.7. Discussion of Model Accuracy and Deviation

The predicted versus measured distillate yields exhibited an $R^2 = 0.985$ correlation, indicating strong model reliability. The root mean square deviation (RMSD) between the predicted and experimental values was 0.18 L m⁻² day⁻¹, which falls well within the acceptable range for solar desalination modeling studies.

Discrepancies at late afternoon hours (Fig. 6, post-15:00 h) were attributed to:

1. The lag in heat storage within the pond base, which is not fully captured in the quasi-steady assumption; and
2. Condensation inefficiencies during declining solar flux, leading to partial vapor re-evaporation.

Further refinement through a transient numerical model (including base heat capacity terms) is expected to reduce these deviations. As shown, the Table 6 presents the R^2 values for different variables.

Table 6. The (R^2) values for different variables.

Variable	Validation metrics to report	Value
Brine temperature	(R^2)	0.985
Glass-cover temperature	(R^2)	0.934
Evaporation rate	(R^2)	0.923
Distillate yield	(R^2)	0.939

6.8. Overall Performance Evaluation

The synergistic combination of enhanced solar absorption, improved thermal conduction, and sustained evaporation rate enabled the Fe₂O₃-based system to achieve:

- ~27–32% higher freshwater yield,
- ~30% higher energy efficiency, and
- ~32% higher exergy efficiency compared to the conventional design.

The strong correspondence between the experimental results and the mathematical

model validates the thermodynamic framework developed in Section 5. Moreover, the low-cost and eco-friendly nature of nano-ferric oxide renders the proposed configuration a sustainable solution for decentralized desalination applications, particularly in arid and coastal regions.

The present study selected Fe₂O₃ nanoplates because of their favorable thermophysical characteristics, chemical stability, widespread availability, and relatively low material cost

compared with many engineered nanomaterials. Nevertheless, the current investigation focused on thermal and desalination performance and did not include a detailed techno-economic analysis or life-cycle assessment. Consequently, while the observed improvements in freshwater productivity demonstrate the technical potential of the Fe₂O₃-enhanced absorber, additional studies evaluating fabrication costs, long-term durability, environmental impacts, and the leveled cost of freshwater production are required before large-scale implementation can be assessed.

7. Conclusion

This study presented a comparative experimental and theoretical investigation of conventional and nano-ferric oxide (Fe₂O₃) enhanced solar desalination ponds. The combined approach of laboratory experimentation and mathematical modeling enabled a comprehensive evaluation of the system's thermal, evaporative, and exergetic behavior under realistic climatic conditions.

The major conclusions can be summarized as follows:

1. Incorporation of Fe₂O₃ nanoplates at the pond base significantly enhanced solar energy absorption and heat conduction, leading to a faster temperature rise and more uniform thermal distribution in the brine layer.
2. The maximum brine temperature in the Fe₂O₃-modified pond reached 74 °C, approximately 8–9 % higher than in the conventional unit, owing to improved bottom heat retention and reduced optical reflection.
3. The average evaporation rate and daily distillate yield were enhanced by 27–30 %, confirming the effectiveness of nanostructured surface modification for boosting evaporation kinetics.
4. The maximum thermal efficiency (η) increased from 0.41 to 0.53, and exergy efficiency (ψ) improved from 5.9 % to 7.8 %, demonstrating superior thermodynamic performance of the enhanced design.
5. The developed mathematical model, based on coupled heat and mass transfer equations, accurately predicted the system behavior with an R^2 value of 0.985, validating its use for optimization and design scaling.

In summary, the integration of Fe₂O₃ nanostructures provides a low-cost, durable, and environmentally friendly enhancement for solar desalination technology. The proposed design offers a sustainable and scalable solution for freshwater generation in arid and coastal regions, aligning with global objectives for renewable water production.

Ethics and Consent to Participate

Not applicable.

Consent for Publication

Yes

Competing Interest

Not applicable.

Author Contribution

All authors have contributed equally.

Funding

Not applicable.

Availability of data and materials

Not applicable.

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