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Development and Performance Evaluation of an Economical Solar Still for Water Purification

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Authors' contributions

This work was carried out in collaboration among all authors. Authors SK, MC and AK designed the study and wrote the first draft of the manuscript. Authors AKA, KKP and PC involved in data curation. Authors SK, MK and CY managed the analyses of the study. Authors SK, MC and AKA helped in literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Aim: The study aims to address the global challenge of clean water scarcity by exploring a cost-effective and efficient solar still for purifying various types of contaminated water using solar energy.
Methodology: An experimental investigation was conducted using a solar still designed with acrylic sheets, an inner mirrored surface, and aluminum fins. The study evaluated the solar still's performance in purifying seawater, brackish water, and polluted water, comparing input and output water quality. The experiments were carried out with and without aluminum fins, using a solar still with an area of 0.25 m².
Results: The solar still successfully reduced the total dissolved solids (TDS), salinity, and pH of the input water. For seawater with an initial TDS of 14,700 PPM, salinity of 18.13 PSU, and pH of 9.15, the output values were 15 PPM TDS, 0.01 PSU salinity, and a pH of 7.4. The highest water volumes were achieved with aluminum fins: 410 ml for seawater, 380 ml for brackish water, and 380 ml for polluted water, compared to 170 ml without fins. The maximum water yield of 1.64 l/m² was achieved for sea water using this solar still.
Conclusion: The study demonstrates that the solar still, particularly when equipped with aluminum fins, effectively transforms high-TDS, high-salinity, and high-pH water into clean, potable water. The findings suggest that solar distillation is a viable solution for producing safe drinking water from contaminated sources.

Keywords: Water purification; solar still; solar energy; sea water; brackish water.

1. INTRODUCTION

Access to clean, potable water is a fundamental necessity for human survival, yet it remains a significant global challenge. Potable water, which is safe for drinking and food preparation, is essential to maintaining health and well-being [1]. However, despite the abundance of water on Earth—over 70% of the planet's surface is covered by water—only a small fraction is accessible and suitable for human consumption. The majority of the Earth's water is found in oceans and is saline, making it unsuitable for drinking without desalination. Moreover, freshwater resources, which constitute less than 3% of the global water supply, are unevenly distributed and often contaminated by pollutants, making them unsafe for direct use [2].

The global water crisis is driven by a combination of factors, including population growth, urbanization, industrialization, and climate change [3]. As the global population continues to rise, the demand for freshwater increases, exacerbating the stress on existing water resources. Industrial activities contribute to the pollution of water bodies with chemicals, heavy metals, and other harmful substances, further reducing the availability of clean water [4,5]. Climate change compounds these challenges by altering precipitation patterns, leading to droughts in some regions and flooding in others, which disrupts the natural replenishment of freshwater sources [6,7].

Traditional water purification methods, such as chemical treatment, filtration, and reverse osmosis, are commonly used to address water contamination [8]. However, these methods often require significant energy inputs, sophisticated infrastructure, and ongoing maintenance, making them expensive and less accessible, especially in remote or underdeveloped regions. Chemical treatment can introduce additional by-products that may pose health risks, while reverse osmosis and other filtration technologies produce brine or waste that must be managed. Furthermore, these methods rely heavily on fossil fuels, contributing to greenhouse gas emissions and exacerbating environmental concerns [9,10,11].

In contrast, solar distillation offers a sustainable and environmentally friendly alternative for water purification. Solar energy, one of the most abundant and renewable energy sources, can be harnessed to purify water through a process that mimics the natural hydrological cycle. The concept of solar distillation dates back to ancient times, with historical records indicating that the Greeks and Romans used rudimentary solar stills to desalinate seawater. However, it was not until the 19th century that modern solar stills were developed, with Charles Wilson pioneering one of the first large-scale solar stills in 1872 in Chile's Atacama Desert. This still was used to provide drinking water for a mining community, producing up to 22,000 liters per day [12,13].

Solar distillation works on the principles of evaporation and condensation. Contaminated water is heated by solar energy, causing it to evaporate. The vapor then condenses on a cooler surface, leaving impurities behind and resulting in clean, distilled water. Solar stills are particularly attractive due to their low operational costs, simplicity, and minimal environmental impact. Over the years, research has focused on improving the efficiency of solar stills through design modifications and the use of innovative materials [14,15].

Tiwari and Suneja [12] analyzed an inverted absorber solar still, demonstrating that optimizing the operating temperature could nearly double the output compared to conventional designs. Singh et al. [16] compared the performance of single and double slope solar stills with various slope angles, finding that single slope designs offered higher energy and exergy efficiency. More recently, Ma et al. [17] explored the use of recycled self-floating black polyurethane sponges as solar absorber materials, significantly increasing evaporation efficiency.

Building on this existing body of research, the current study aimed to develop and evaluate a low-cost, energy-efficient solar still designed for the purification of various types of contaminated water, including seawater, brackish water, and polluted water. The solar still constructed in this study featured an acrylic sheet structure with an inner mirrored surface to maximize solar energy absorption. Additionally, aluminum fins were incorporated into the design to enhance heat transfer efficiency, thereby increasing the rate of evaporation and overall water yield.

2. MATERIALS AND METHODS

2.1 Description of the Experimental Set Up

The structural components of the solar still were fabricated in the department of Agricultural and Food Engineering, IIT Kharagpur, India, to ensure that no water leakage occurred during the experiment. To verify the integrity of the structure, the solar still was filled to its maximum capacity with water and left for 48 hours with the aluminum plate in place. The structural parts were constructed using acrylic sheets, with the dimensions detailed in Table 1. The acrylic sheets, glass, and mirrors were precisely cut according to the specified dimensions. The aluminum sheets were fabricated to ensure they did not come into contact with the inner sides of the solar still's walls. Holes were drilled into the aluminum sheets, and aluminum wire was threaded through these holes, then secured using Araldite adhesive, which was allowed to cure for 24 hours. After this, the mirrors were affixed to the inner surfaces of the side plates with the reflective side facing inward. Finally, the four side plates were attached to the base plate using a cementing agent made from a mixture of alcohol and Fevikwik, ensuring a secure and leak-proof assembly. Reflecting mirrors was used inside walls of the still (i.e. back and sides) in order to minimize the amount of energy lost and aluminium fin was used to store the heat which help in heating the water and to check the effect of aluminium fin in water evaporation. The CAD model of the side wall with dimensions is shown in Fig. 1. CAD models of the aluminum fin arrangement and solar still are depicted in Fig. 2 (a) and (b). The developed solar still is shown in Fig. 3. All the experiments were carried out with and without aluminium fin for different types of water (sea water, brackish water and polluted water).

2.2 Water Quality Parameters Measurement

The procedure for measuring the initial and final water quality parameters involved a comprehensive analysis of the physical, chemical, and biological characteristics of the water samples. This analysis was conducted both before the experiment commenced and after its completion to evaluate the effectiveness of the solar still in purifying the water (Table 2). The water samples used in the experiment were sourced from seawater, brackish water, and polluted water. The quality of these samples, as well as the distilled water produced by the solar still, was assessed based on several key parameters. These included pH, Total Dissolved Solids (TDS in PPM), temperature (in °C), pressure (in psi), salinity (in PSU), and dissolved oxygen (DO). The measurements were taken to ensure accurate and reliable data, allowing for a detailed comparison of the water quality before and after the distillation process. The measurements of pH, TDS, temperature, pressure, salinity, and DO were conducted using calibrated instruments to ensure precision. These instruments were regularly checked and maintained to avoid any potential discrepancies in the data. The pH levels were determined using a digital pH meter, while TDS was measured with a TDS meter. Temperature and pressure were monitored with thermometer and pressure gauge, and salinity was measured using a salinity meter. Dissolved oxygen levels were measured using a DO meter, which was calibrated before each use. This comprehensive analysis of the water quality parameters allowed for a thorough assessment of the solar still's performance in producing clean, potable water from contaminated sources.

Table 1. Description of material used in fabrication of solar still

S.N.	Component	Material uses	Dimension	Number of pieces
1	Base plate	Acrylic sheet	509 × 509 mm	1
2	Front plate	Acrylic sheet	509 × 50 mm	1
3	Back plate	Acrylic sheet	509 × 232 mm	1
4	Side plate	Acrylic sheet	509 × 50 × 232 mm	2
5	Inner front plate	Mirror	469 × 30 mm	1
6	Inner back plate	Mirror	409 × 182 mm	1
7	Inner side plate	Mirror	469 × 30 × 194 mm	2
8	Aluminium fin	Aluminium sheet	450 × 450 mm	1

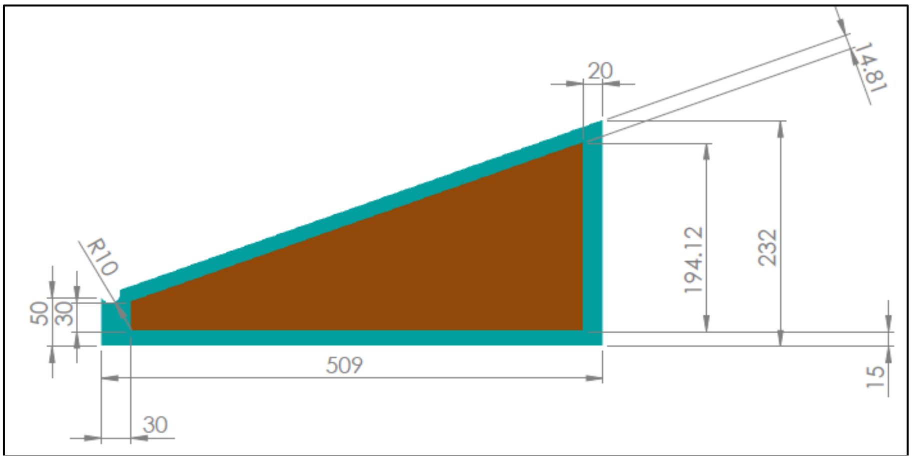

Fig. 1. CAD model of the sidewall of the solar still with dimensions (all dimensions are in mm)

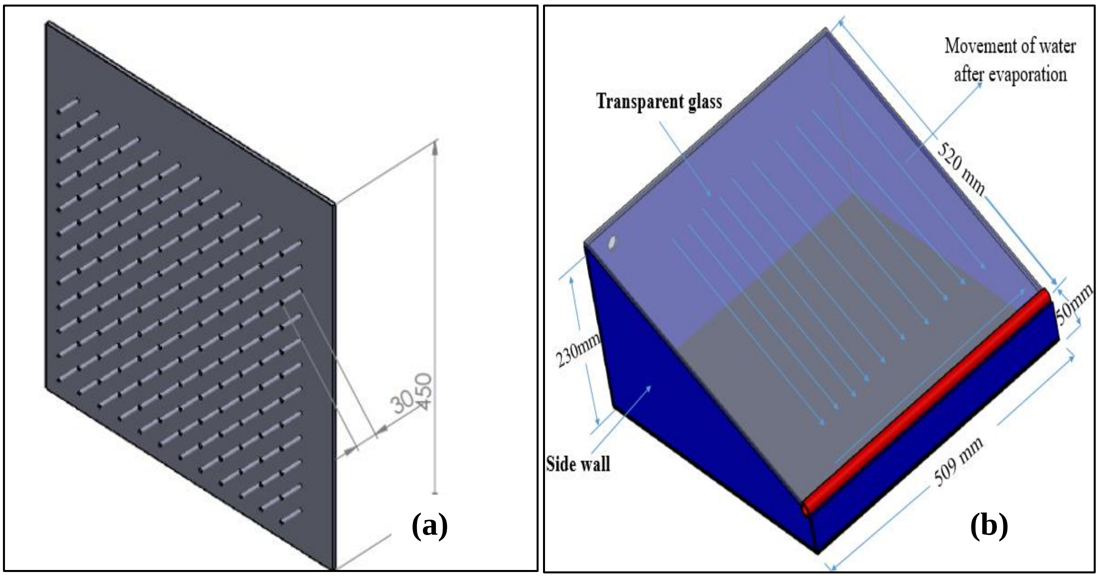

Fig. 2. (a) CAD model of aluminum fin arrangement (b) CAD model of solar still

Fig. 3. Developed solar still

Table 2. Comparison of input water quality and Indian Standards

Parameter	Sea water	Brackish water	Polluted water	Indian Standards
Ph	9.15	8.52	12	6.5-8.5
TDS (PPM)	14700	7256	7800	500 Max
Temperature (°C)	26.45	26.45	26.45	-
Pressure (psi)	14.66	14.66	14.66	-
Salinity (PSU)	18.13	8.4	5	0.3-1
DO	17.65	15.73	8	6.5-9

2.3 Performance Evaluation of the Solar Still

The performance evaluation of the solar still was carried out by analyzing the yield in relation to environmental parameters, as well as by assessing certain quality parameters of both the input and output water. The study focused on three types of water samples: seawater, brackish water, and polluted water. The experiments were conducted under two distinct conditions to thoroughly evaluate the solar still's efficiency and effectiveness. In the first condition, the experimental procedure involved using an aluminum sheet to measure the quantity of distilled water accumulated at 5 PM each day. This phase of the experiment was structured into three separate intervals, each dedicated to one of the water samples. The first interval involved measuring the distillate yield from seawater over a period of five days. Following this, the same process was applied to brackish water during the next five days. The final five-day interval was focused on polluted water. For each type of water, the accumulated water yield was carefully measured and recorded at the end of each day to assess the solar still’s performance under consistent conditions. In the second condition, the experiment was designed to compare the effects of the aluminum sheet on water accumulation. This phase lasted four days for each water sample—seawater, brackish water, and polluted water. The four-day period was divided into two segments. During the first two days, the water yield was measured with the aluminum sheet in place. For the remaining two days, the aluminum sheet was removed to determine its impact on the distillation process.

This procedure was systematically applied to each type of water to ensure a thorough comparison between the two conditions. Several performance metrics were used to evaluate the solar still. The distillate yield, which is the amount of distilled water produced per unit area or time, was a key metric. Efficiency was also calculated as the ratio of the distilled water produced to the amount of solar energy received by the still. Additionally, the quality of the distillate was assessed by measuring the purity and detecting any contaminants in the distilled water, with these analyses conducted in an aquaculture lab. Environmental data necessary for the performance evaluation, such as temperature, humidity, and solar radiation, was obtained from the meteorological section of IIT Kharagpur. All the data collected throughout the experiment was meticulously analyzed using Microsoft Excel, enabling a detailed assessment of the solar still's performance across different conditions and water types. This comprehensive evaluation provided valuable insights into the effectiveness of the solar still design and the role of the aluminum sheet in enhancing water distillation.

3. RESULTS AND DISCUSSION

3.1 Weather Parameters During Experimentation

Variation of environmental parameter and solar intensity obtained at different day of experiment is shown in Fig. 4 and Fig. 5 respectively. The data revealed a direct correlation between the amount of distilled water produced and the intensity of solar radiation. As solar intensity increased, the yield of clean water also increased, and conversely, as solar intensity decreased, the water yield diminished. However, variations in other environmental parameters, such as temperature and humidity, also influenced the results, leading to occasional deviations from this trend. For instance, on the fifth day of the seawater experiment, the solar intensity decreased, but the amount of clean water produced actually increased. This anomaly can be attributed to a combination of environmental factors: on that day, the maximum temperature was high, the minimum temperature was low, and both the maximum and minimum relative humidity levels decreased significantly. These conditions likely enhanced the evaporation and condensation processes, resulting in an increased yield of distilled water despite the lower solar intensity. This analysis underscores the complex interplay between solar radiation and environmental conditions in determining the efficiency of the solar still. While solar intensity is a primary driver of water production, other factors such as temperature and humidity can also have a significant impact, occasionally leading to unexpected results.

3.2 Performance Evaluation of the Solar Still with Different Water Types and fins

The experiment was conducted over 15 days to evaluate the performance of the solar still using three different water types—seawater, brackish water, and polluted water—under two conditions: with and without aluminum fins. The results of the water quantity produced by the solar still were measured daily and revealed interesting insights into the effectiveness of the aluminum fins in enhancing water yield (Fig. 6). During the first five days, seawater was used as the input. The solar still produced varying amounts of distilled water, with and without fins. On Day 1, the water yield was slightly higher without fins (410 ml) compared to with fins (365 ml). This trend was observed on Day 2 as well, where the still without fins produced 380 ml of water, compared to 265 ml with fins. However, on Days 3 and 4, the presence of fins did not significantly enhance the yield, with both conditions yielding similar amounts (190-270 ml). By Day 5, the water quantity increased to 330 ml with fins and 380 ml without fins, suggesting that the fins may have a more complex interaction with the solar still's performance depending on the day-to-day environmental conditions. For brackish water, tested between Days 6 and 10, the results were mixed. On Day 6, the solar still with fins produced 350 ml, slightly less than the 360 ml obtained without fins. This pattern of slightly higher yields without fins continued on Day 7. Interestingly, on Day 8, the yield with fins remained consistent at 280 ml, while without fins, it dropped to 190 ml. This could indicate that the fins might stabilize the output under certain conditions. However, on Day 9, the yield was almost equal, with 330 ml produced with fins and 350 ml without fins. On Day 10, the solar still without fins showed a higher output (370 ml) compared to with fins (280 ml), suggesting that under certain conditions, the fins might impede rather than enhance water production. The final phase of the experiment involved polluted water, tested from Day 11 to Day 15. Here, the results were more varied. On Day 11, the yield with fins was higher (310 ml) compared to without fins (210 ml). This trend reversed on Day 12, with

370 ml produced with fins and 200 ml without fins, indicating a significant enhancement due to the fins. However, on Days 13 and 14, the yields were higher with fins (380 ml and 230 ml, respectively) compared to without fins (190 ml and 185 ml). On the final day, Day 15, the yield remained higher with fins (350 ml) than without fins (180 ml). The results suggest that the use of aluminum fins in the solar still generally enhanced water production, particularly with polluted water. The maximum water yield of 1.64 l/m^2 was achieved for sea water using this solar still. However, the effect was not consistent across all types of water and all days. The variability in results may be attributed to environmental factors such as temperature fluctuations, solar intensity, and humidity, which can influence the efficiency of the evaporation and condensation processes within the solar still. These findings indicate that while aluminum fins have the potential to improve the performance of a solar still, their effectiveness may depend on specific operational conditions and the type of water being processed.

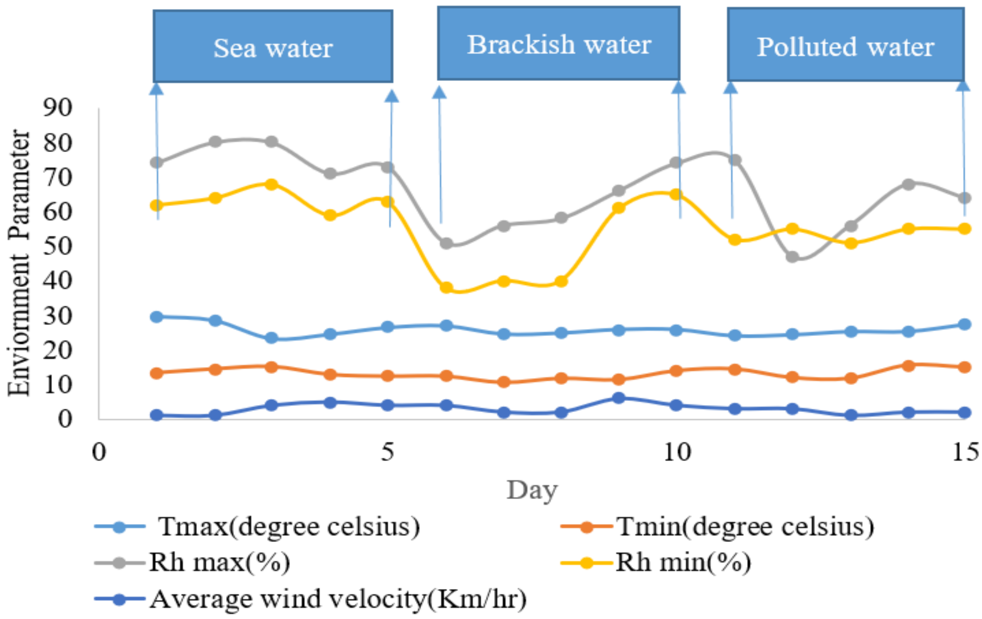

Fig. 4. Environmental parameter distribution profile with respect to day

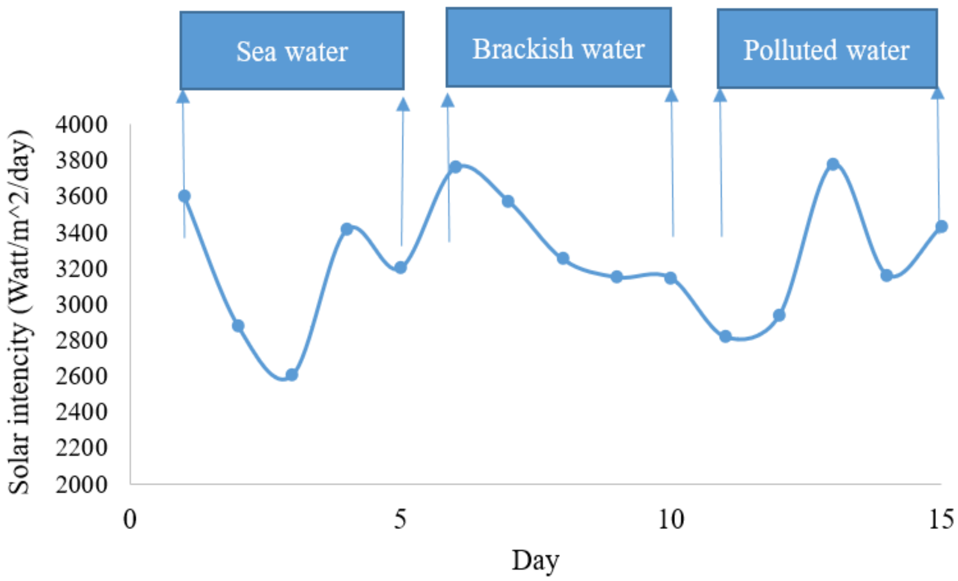

Fig. 5. Solar intensity distribution profile with respect to day

Table 3. Comparison of output water quality and indian standards

	Obtained Water (Sea) fins	Obtained Water (Sea) Without fins	Obtained Water (brackish water) fins	Obtained Water (brackish water) without fins	Obtained Water (polluted) fins	Obtained Water (polluted) without fins	Indian Standards
pH	7.4	7.32	7.7	7.2	7.6	7.5	6.5-8.5
TDS (PPM)	15	17	12	13	30	31	500 Max
Temperature (ºC)	24	24	22	22	22.5	22.5	-
Pressure (psi)	14.69	14.69	14.7	14.7	14.7	14.7	-
Salinity (PSU)	0.01	0.01	0.01	0.01	0.02	0.03	0.3-1
DO	9.1	9.12	7.5	7.6	10.2	10.3	6.5-9

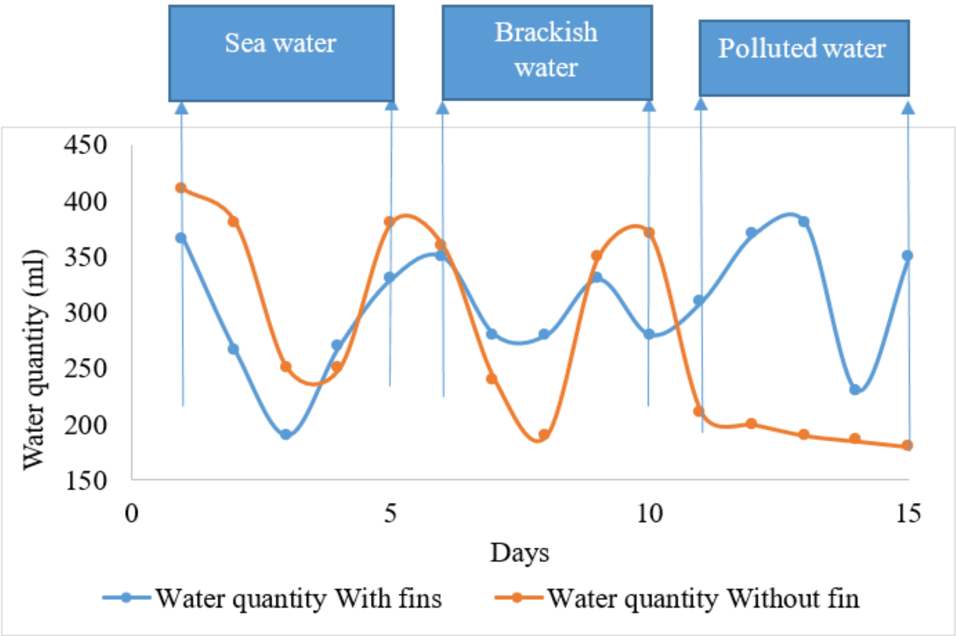

Fig. 6 Measured output water quantity distribution profile with respect to day

3.3 Analysis of Water Quality

The analysis of water quality was conducted to evaluate the effectiveness of the solar still in improving the quality of water from different sources, namely seawater, brackish water, and polluted water. The distilled water obtained under two conditions: with and without aluminum fins, was assessed based on key parameters such as pH, Total Dissolved Solids (TDS), temperature, pressure, salinity, and Dissolved Oxygen (DO). The results were compared against the Indian Standard specifications to determine the quality and suitability of the distilled water (Table 3). For seawater, the solar still significantly improved the water quality. The pH of the distilled water was 7.4 with fins and 7.32 without fins, both within the acceptable range of 6.5 to 8.5 as specified by Indian Standards. The TDS levels were notably reduced, with the distilled water showing 15 PPM with fins and 17 PPM without fins, far below the maximum permissible limit of 500 PPM. This substantial reduction in dissolved solids indicates that the solar still effectively purifies seawater, making it suitable for consumption and other uses. The temperature of the distilled water remained constant at 24°C under both conditions, and the pressure was measured at 14.69 psi, indicating stable conditions within the still. Salinity was drastically reduced to 0.01 PSU in both cases, far below the acceptable range of 0.3 to 1 PSU, demonstrating the still's efficiency in desalination. Additionally, the Dissolved Oxygen (DO) levels were slightly higher with fins (9.1 mg/L) compared to without fins (9.12 mg/L), both exceeding the minimum required level of 6.5 mg/L, confirming the high oxygen content and overall quality of the distilled water. In the case of brackish water, the distilled water also exhibited improved quality. The pH levels were 7.7 with fins and 7.2 without fins, both within the acceptable limits, indicating a neutral to slightly alkaline nature suitable for drinking. The TDS levels were reduced to 12 PPM with fins and 13 PPM without fins, significantly below the 500 PPM limit, showing the solar still's effectiveness in reducing dissolved solids in brackish water. The temperature of the distilled water was stable at 22°C, and the pressure was consistent at 14.7 psi, suggesting that the operating conditions of the still were well-maintained. Salinity levels were reduced to 0.01 PSU in both conditions, well within the acceptable range, further highlighting the still's ability to desalinate water. The DO levels were 7.5 mg/L with fins and 7.6 mg/L without fins, both within the optimal range, ensuring the water's suitability for drinking and other applications. For polluted water, the solar still again demonstrated its capacity to improve water quality. The pH of the distilled water was 7.6 with fins and 7.5 without fins, both within the acceptable range, indicating the water's neutrality and safety for consumption. The TDS levels were slightly higher compared to seawater and brackish water but remained well below the maximum allowable limit, with 30 PPM with fins and 31 PPM without fins. This suggests that the solar still was effective in reducing the concentration of dissolved solids even in more heavily polluted water. The temperature of the distilled water was 22.5°C in both conditions, and the pressure was maintained at 14.7 psi, indicating consistent performance of the still. Salinity levels were slightly higher than in the other water types, with 0.02 PSU with fins and 0.03 PSU without fins, but still significantly lower than the maximum permissible range, ensuring the water's suitability for use. The DO levels were notably higher in this case, with 10.2 mg/L with fins and 10.3 mg/L without fins, reflecting the high oxygen content and overall improved quality of the distilled water.

3.4 Cost Estimation

The cost estimation for the desalination process using the solar still primarily hinges on the expenses associated with materials, manufacturing, and maintenance, given that the energy source—the sun—is freely available. As a result, the overall cost of producing distilled water is largely dependent on the materials used in constructing the solar still. A detailed breakdown of the material costs is provided in Table 4. Table 4 outlines the costs of the various materials required to fabricate the solar still. The largest expense is attributed to the acrylic sheet, which costs Rs. 2000.00, reflecting its importance as the primary structural component of the still. Mirrors, which are essential for enhancing the reflective properties within the still, contribute Rs. 600.00 to the total cost. The transparent glass, crucial for allowing sunlight to enter the still while retaining heat, costs Rs. 250.00. Adhesive materials, including Araldite and Fevikwik, which are necessary for securely assembling the still's components, add Rs. 250.00 and Rs. 100.00 to the cost, respectively. The aluminum wire and sheet, used for structural support and increasing the efficiency of the still, cost Rs. 50.00 and Rs. 500.00, respectively. Lastly, the PVC pipe, which facilitates the flow of water within the system, adds a minimal cost of Rs. 50.00. In total, the cost of materials for constructing the solar still amounts to Rs. 3550.00. This estimation highlights the affordability of building a solar still, particularly given that the operational energy is derived entirely from solar radiation, which incurs no additional cost. The cost-effectiveness of this system, combined with its ability to provide clean water, makes it a viable solution for addressing water scarcity in regions where conventional desalination methods may be prohibitively expensive.

Table 4. Manufacturing costs of solar still

Material	Cost (Rs)
Acrylic sheet	2000.00
Mirror	600.00
Transparent glass	250.00
Araldite	250
Fevikwik	100
Aluminium wire	50
Aluminium sheet	500
PVC Pipe	50
Total	3550.00

4. CONCLUSIONS

Water and energy are fundamental to our daily lives, and solar energy offers a limitless, cost-free, and eco-friendly solution. Solar stills effectively purified different types of water to provide safe drinking water using sunlight as their sole energy source, unlike many commercial systems that rely on electricity or fossil fuels. Solar distillation achieved comparable water quality to other distillation methods but with the added benefit of using renewable energy. Enhancements, such as aluminum fins in solar stills, can improve efficiency by increasing kinetic energy and evaporation even at lower temperatures. While maximum evaporation is not solely dependent on temperature, the intensity of sunlight and relative humidity play crucial roles. Increased sunlight intensity boosts kinetic energy and evaporation rates, while high relative humidity can reduce evaporation. Overall, solar stills can be optimized to achieve both maximum and minimum water output efficiently.

The solar still's limitations include its relatively low water yield and dependency on consistent solar radiation, which can impact performance under variable weather conditions. Future research should explore advanced materials like nanomaterials for better heat absorption and conductivity in solar stills. Integrating alternative energy sources, such as photovoltaics, could enhance efficiency during low-sunlight periods. Additionally, applying AI or machine learning to optimize performance and experimenting with multi-stage or hybrid designs could significantly improve water yield and purification efficiency.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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