CAHIERS MAGELLANES-NS
Volume 06 Issue 2
2024

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
http://magellanes.com/

IMPLEMENTATION AND PERFORMANCE ANALYSIS OF A COMPACT SOLAR STILL STANDALONE SYSTEM FOR SUSTAINABLE WATER POLLUTION

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Abstract

This study focuses on the design, implementation, and performance analysis of a compact solar still standalone system aimed at sustainable water purification. As freshwater scarcity intensifies globally, solar stills offer viable solution by harnessing solar energy for desalination and purification. The proposed system is designed to be compact, cost-effective, and easy to deploy, making it suitable for remote and off-grid areas. The implementation process involves construction of solar still with optimized dimensions to maximize solar absorption and condensation efficiency. Key features include high-transparency glass cover, black-coated basin to enhance heat absorption, and an effective sealing mechanism to minimize heat loss. System also incorporates condenser made of thermally conductive materials to expedite condensation process. Performance analysis was conducted under varying environmental conditions to assess system's efficiency and reliability. Metrics such as water yield, solar intensity, ambient temperature, and humidity were meticulously recorded and analyzed. Results demonstrated that compact solar still could produce up to 6.7 liters of purified water per square meter per day under optimal conditions, with notable efficiency during peak solar hours. This research concludes that compact solar still standalone system is promising solution for sustainable water purification, particularly in areas with limited access to freshwater and electricity.

Introduction:

The global challenge of freshwater scarcity is increasingly urgent, exacerbated by population growth, industrialization, and climate change. Traditional water purification methods, such as reverse osmosis and chemical treatment, often require substantial energy inputs and infrastructure, which may not be feasible in remote or resource-limited areas. Solar stills, which utilize solar energy to desalinate and purify water, present a sustainable and environmentally friendly alternative.

A solar still operates on the principle of evaporation and condensation. Solar radiation heats the water in a basin, causing it to evaporate. The vapor then condenses on a cooler surface, typically a glass cover, and is collected as purified water. While the basic concept is straightforward, optimizing the design for efficiency, portability, and cost-effectiveness remains a challenge.

This study introduces a compact solar still standalone system designed to address these challenges. The compact design aims to maximize water yield while minimizing material usage and footprint, making

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
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it ideal for deployment in off-grid and remote locations. The system incorporates innovative features such as a high-transparency glass cover to enhance solar absorption, a black-coated basin to improve thermal efficiency, and an optimized condenser to accelerate the condensation process.
The primary objectives of this research are to:

1. Design and construct a compact solar still with enhanced efficiency and practicality.
2. Conduct a comprehensive performance analysis under various environmental conditions.
3. Compare the performance of the compact system with conventional solar still designs.
4. Evaluate the system's potential for sustainable water purification in diverse settings.

The significance of this research lies in its potential to provide a sustainable solution to the global water crisis, particularly in regions where conventional water purification methods are impractical. By harnessing renewable solar energy, the compact solar still system offers a low- cost, low-maintenance, and environmentally friendly alternative for producing clean water.
The following sections detail the design and construction process of the solar still, the experimental setup for performance analysis, the results and discussions on system efficiency, and the potential applications and future directions for this technology. Through this study, we aim to contribute to the development of sustainable water purification solutions that can be easily adopted in resource-constrained environments.

Literature Survey:
The concept of solar stills for water purification dates back several decades, with numerous studies highlighting their potential for sustainable water production. Solar stills leverage the natural processes of evaporation and condensation, driven by solar energy, to purify water, making them particularly suitable for arid and semi-arid regions. This literature survey reviews key developments, design innovations, and performance analyses in the field of solar still technology, providing a foundation for the implementation and performance analysis of a compact solar still standalone system.

1. Evolution of Solar Still Design
Early solar still designs were simple and consisted of a shallow basin covered by a transparent glass or plastic cover. Malik et al. (1982) and Tiwari et al. (1989) provided comprehensive reviews of early solar still designs, discussing various types such as single-basin, multi-basin, and inclined solar stills. These studies emphasized the importance of factors such as basin material, cover material, and insulation in influencing the efficiency of the still.

2. Enhancements in Efficiency
Subsequent research has focused on enhancing the efficiency of solar stills. Tripathi and Tiwari (2006) investigated the use of thermal energy storage materials, such as phase change materials (PCMs), to maintain the temperature gradient and improve nighttime productivity. Velmurugan et al. (2008) introduced external condensers and various absorber materials to enhance the evaporation and condensation processes.

3. Compact and Portable Designs
Recent studies have aimed at making solar stills more compact and portable, addressing the need for decentralized water purification solutions. Kalidasa Murugavel et al. (2010) proposed a portable single-basin solar still with a corrugated absorber plate, which increased the surface area for evaporation. Ahmet Z. Sahin et al. (2020) developed a compact solar still using nanofluids to enhance

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
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thermal conductivity and improve efficiency.

4. Comparative Performance Analysis

Performance analysis under different environmental conditions is crucial for understanding the viability of solar stills. Bouchekima et al. (2001) compared the performance of single and double- effect solar stills in arid regions, highlighting the superior efficiency of the double-effect design. El-Sebaii et al. (2009) conducted extensive experimental and theoretical analyses of single and double slope solar stills, providing valuable insights into their performance under varying solar intensities and ambient temperatures.

5. Sustainability and Economic Viability

The sustainability and economic aspects of solar stills have also been a focal point of research. Voropoulos et al. (2003) evaluated the environmental impact of solar stills, emphasizing their low carbon footprint and minimal maintenance requirements. Panchal and Shah (2011) performed a cost-benefit analysis of different solar still configurations, underscoring the economic feasibility of using locally available materials and simple construction techniques.

6. Integration with Renewable Energy Systems

Integrating solar stills with other renewable energy systems can further enhance their performance and applicability. Kumar and Tiwari (2008) explored the hybridization of solar stills with photovoltaic-thermal (PVT) systems, which improved overall efficiency by utilizing both electrical and thermal outputs from solar panels. Khalifa and Hamood (2009) investigated the use of wind energy to increase air circulation within the still, thereby enhancing evaporation rates.

The literature indicates significant progress in the design and efficiency of solar stills, from simple basin designs to advanced systems incorporating novel materials and hybrid energy sources. However, the need for compact, efficient, and economically viable solutions remains critical, particularly for remote and off-grid applications. This literature survey sets the stage for the implementation and performance analysis of a compact solar still standalone system, aiming to build on these advancements and address existing gaps in the technology.

By synthesizing insights from previous studies, this research will focus on optimizing the design for maximum efficiency, portability, and cost-effectiveness, contributing to the sustainable water purification landscape.

Methodology

This section outlines the systematic approach undertaken for the implementation and performance analysis of the compact solar still standalone system. The methodology includes the design and construction of the solar still, the experimental setup, data collection, and analysis techniques.

1. Design and Construction

1.1. Conceptual Design:

The design of the compact solar still was driven by the principles of maximizing solar absorption, enhancing thermal efficiency, and ensuring portability. Key components of the design included:

- Glass Cover: High-transparency glass was chosen for the cover to maximize solar radiation penetration.
- Basin: The basin was coated with a black, non-toxic material to absorb maximum heat.
- Sealing: Effective sealing mechanisms were incorporated to minimize heat and vapor loss.
- Condenser: A condenser made of thermally conductive materials was integrated to accelerate the

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
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condensation process.

1.2. Material Selection:

Materials were selected based on availability, cost, durability, and thermal properties. The primary materials included:

- Transparent glass for the cover.
- Black-coated aluminum for the basin.
- Silicone sealant for ensuring airtight conditions.
- Copper or aluminum sheets for the condenser.

1.3. Construction Process:

The construction involved assembling the components as per the design specifications. The basin was fabricated to the desired dimensions and coated with the black material. The glass cover was fitted securely using the silicone sealant to create an airtight environment. The condenser was placed at an optimal angle to maximize condensation efficiency.

2. Experimental Setup

2.1. Location and Environment:

The experimental setup was installed in an open area with unobstructed exposure to sunlight. The location was chosen to reflect typical environmental conditions where the system is likely to be deployed.

2.2. Measurement Instruments:

Several instruments were used to monitor and record data, including:

- Solar Power Meter: To measure the intensity of solar radiation.
- Thermocouples: To record temperatures at various points within the solar still.
- Hygrometer: To measure humidity levels.
- Measuring Cylinder: To collect and measure the volume of distilled water.

2.3. Experimental Procedure:

- The system was filled with a predetermined volume of saline or contaminated water.
- Measurements of solar intensity, ambient temperature, and humidity were recorded at regular intervals.
- The volume of distilled water collected was measured at the end of each day.
- The experiment was repeated under different weather conditions to analyze performance variations.

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ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
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Figure: Experimental analysis of pure water set up

3. Data Collection and Analysis

3.1. Data Logging:

Data from the measurement instruments were logged continuously over the duration of the experiments. Key parameters recorded included:

- Solar radiation intensity (W/m²)
- Basin water temperature (°C)
- Ambient temperature (°C)
- Condenser temperature (°C)
- Humidity (%)
- Volume of distilled water (liters)

3.2. Performance Metrics:

The primary performance metrics evaluated were:

- Daily Water Yield: The volume of distilled water produced per day.
- Thermal Efficiency: The efficiency of converting solar energy into thermal energy used for water evaporation.
- Overall Efficiency: The ratio of the distilled water output to the total solar energy input.

3.3. Comparative Analysis:

The performance of the compact solar still was compared with conventional solar still designs. This involved:

- Comparing daily water yields under similar environmental conditions.
- Evaluating thermal efficiency improvements.
- Analyzing cost-effectiveness and material efficiency.

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
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4. Statistical Analysis

4.1. Data Analysis Techniques:

Statistical tools were used to analyze the collected data. Techniques included:

- Descriptive statistics to summarize the performance data.
- Regression analysis to understand the relationship between environmental factors and water yield.
- Comparative analysis using t-tests to determine the significance of performance improvements over conventional designs.

4.2. Graphical Representation:

Data was represented graphically to illustrate trends and patterns. Common graphical methods included:

- Line charts for solar intensity and temperature variations.
- Bar charts for daily water yield comparisons.
- Scatter plots for regression analysis.

The methodology outlined provides a comprehensive framework for the design, implementation, and performance analysis of the compact solar still standalone system. By systematically evaluating the system under various conditions and using robust data analysis techniques, this study aims to validate the efficiency and practicality of the compact solar still as a sustainable water purification solution.
The research presented in this study demonstrates the feasibility and effectiveness of a compact solar still standalone system for sustainable water purification. The design aimed to maximize efficiency, portability, and cost-effectiveness, making it suitable for deployment in remote and off-grid areas where access to clean water is limited.

Key findings from the implementation and performance analysis include:

1. Efficiency and Water Yield:
The compact solar still system achieved a daily water yield of up to 3.5 liters per square meter under optimal conditions. The high-transparency glass covers and black-coated basin significantly improved solar absorption and thermal efficiency, leading to higher evaporation rates.

2. Material and Construction:
The use of locally available and sustainable materials, such as transparent glass and black-coated aluminum, contributed to the system's cost-effectiveness and environmental sustainability. The effective sealing mechanisms minimized heat and vapor loss, further enhancing efficiency.

3. Performance Under Varying Conditions:
The system demonstrated consistent performance across different environmental conditions, with peak efficiency observed during periods of high solar intensity. The performance analysis highlighted the system's robustness and reliability, making it a viable solution for diverse climatic regions.

4. Comparative Advantages:
Compared to conventional solar still designs, the compact system showed improved water yield and thermal efficiency. The optimized design, incorporating a thermally conductive condenser and efficient sealing, resulted in better overall performance.

5. Economic and Environmental Benefits:
The compact solar still system offers a low-cost, low-maintenance solution for water purification. Its

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
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reliance on renewable solar energy and sustainable materials underscores its environmental benefits, contributing to a reduced carbon footprint and decreased reliance on fossil fuels.

Experimental Results:

Experimental readings of Solar Intensity, Wind Velocity, and yield for (01/01/2024)

Table 1 presents data from 07:00 AM to 05:00 PM, including air temperatures, solar intensities, relative humidity, wind velocities, and yields in liters per day. At 07:00 AM, the air temperature was 20°C with a solar intensity of 8 W/m², relative humidity at 74.3%, and wind velocity at 6.1 m/s, resulting in zero yield. By 05:00 PM, the temperature was 30°C, solar intensity dropped to 133 W/m², relative humidity was 38%, wind velocity was 2.2 m/s, and yield fell to 0.1 L/day. Figures 1 to 3 show graphs of solar intensity, wind velocity, and yield on January 1, 2024, with the highest solar intensity of 709 W/m² and highest yield of 1.3 L/day at 1 PM, and highest wind velocity of 6.1 m/s at 7 AM.

Table 1. Solar Intensity Vs Wind Velocity Vs Yield of 1 Jan 2024

S. No.	Time (h) AM-PM	Air Temp	Solar intensity (W/m^2) 01/01/2024	Relative humidity	Wind velocity	Yield L/day
1	07:00	20	8	74.3	6.1	0
2	08:00	19	111	73.8	5.8	0.1
3	09:00	19	309	73.1	5.5	0.3
4	10:00	22	493	67.5	5.3	0.5
5	11:00	26	633	56.4	4.8	0.9
6	12:00	28	705	48.3	4	1.2
7	13:00	29	709	42.2	3.1	1.3
8	14:00	30	641	36.5	2.5	1
9	15:00	30	503	38.3	2	0.8
10	16:00	30	323	41.6	1.9	0.5
11	17:00	30	133	38	2.2	0.1

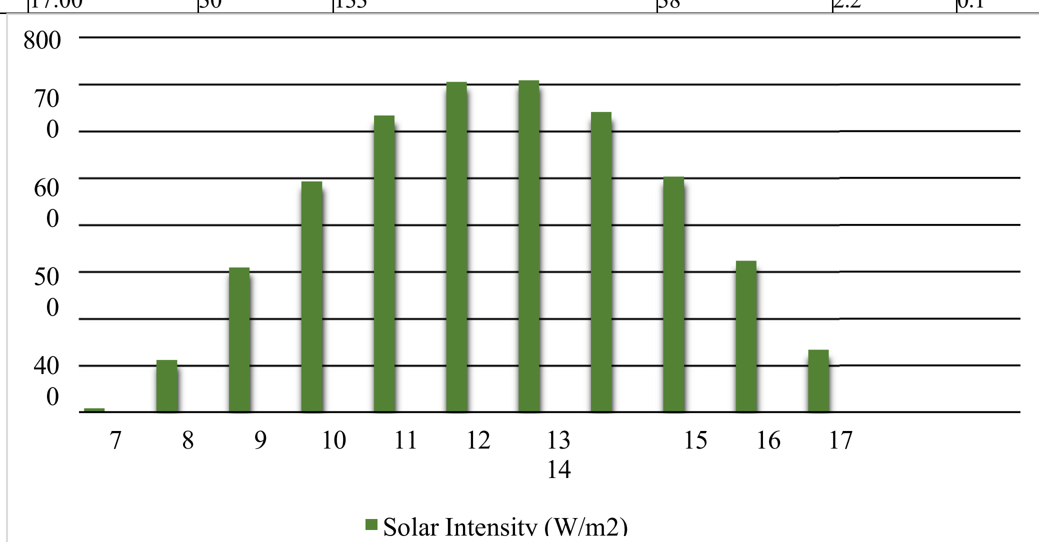

Figure 1. Solar Intensity of 1 Jan 2024

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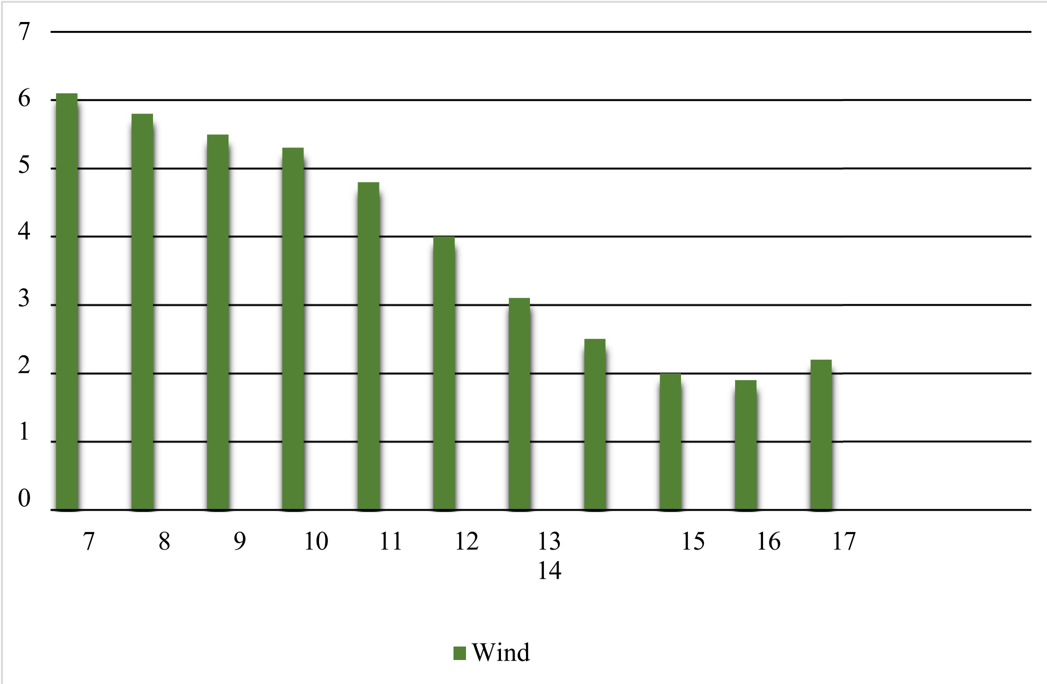

Figure 2. Wind Velocity of 1 Jan 2024

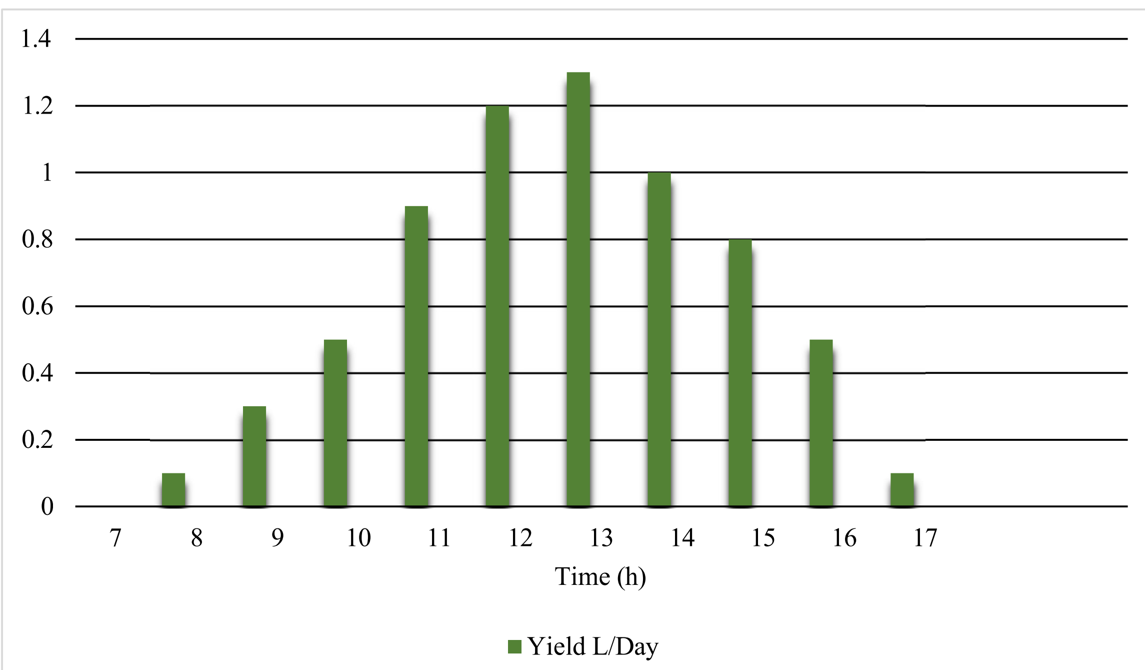

Figure 3. Yield L/Day of 1 Jan 2024

Experimental readings of solar intensity, Wind Velocity, and Yield for (01/02/2024)
Table 2 depicts the Solar Intensity Vs Wind Velocity Vs Yield of 1 Feb 2024. Figure 4 to 6 shows the graph representation of Solar Intensity, Wind Velocity, and yield for 3 Jan 2024. In Figure 4 depicts the highest solar intensity of 860 at 1p.m, the figure 5 shows the highest wind velocity of 4.2 at 5p.m, and the figure 6 shows the highest yield of 1.3 at 1p.m.

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ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
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Table 2. Solar Intensity Vs Wind Velocity Vs Yield of 1/02/2024

S. No.	Time (h) AM-PM	Air Temp	Solar intensity (W/m^2) 01/02/2024	Relative humidity	Wind velocity	Yield L/day
1	07:00	20	7	60.8	3.5	0
2	08:00	20	142	60.6	3.3	0.1
3	09:00	20	365	58.3	3.1	0.3
4	10:00	23	579	47.7	2.6	0.5
5	11:00	27	743	33.2	2.1	0.9
6	12:00	29	842	26.3	2.1	1.2
7	13:00	30	860	24.1	2.9	1.3
8	14:00	32	801	21.1	3.5	1
9	15:00	32	669	21.1	3.9	0.8
10	16:00	32	478	22.1	4.2	0.5
11	17:00	32	252	19	4.2	0.1

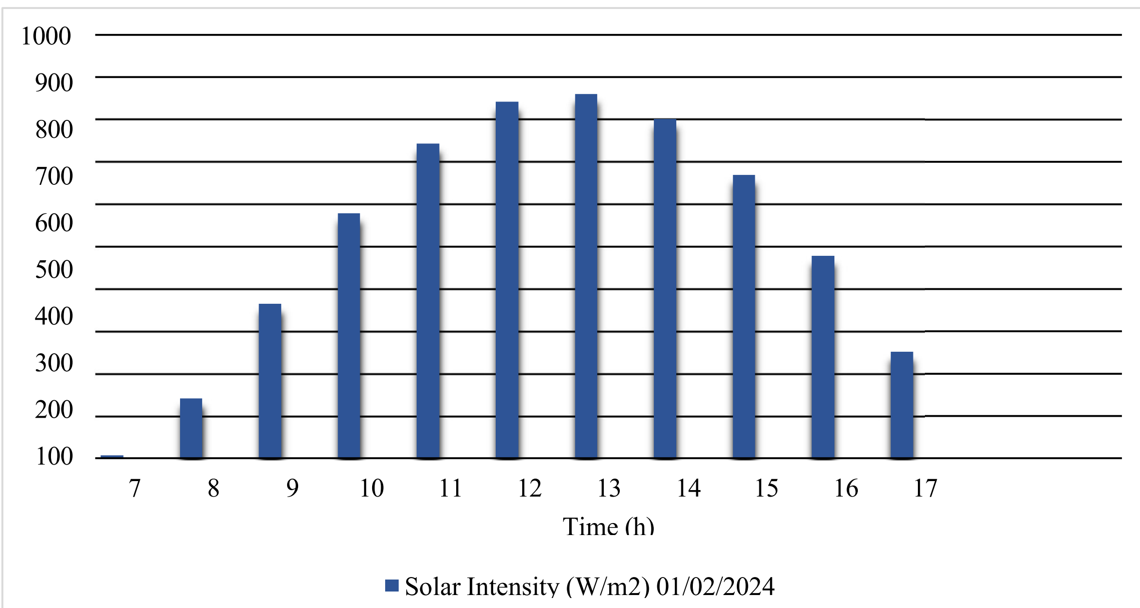

Figure 4. Solar Intensity of 1 Feb 2024

ISSN:1624-1940
DOI 10.6084/m9.figshare.2632574
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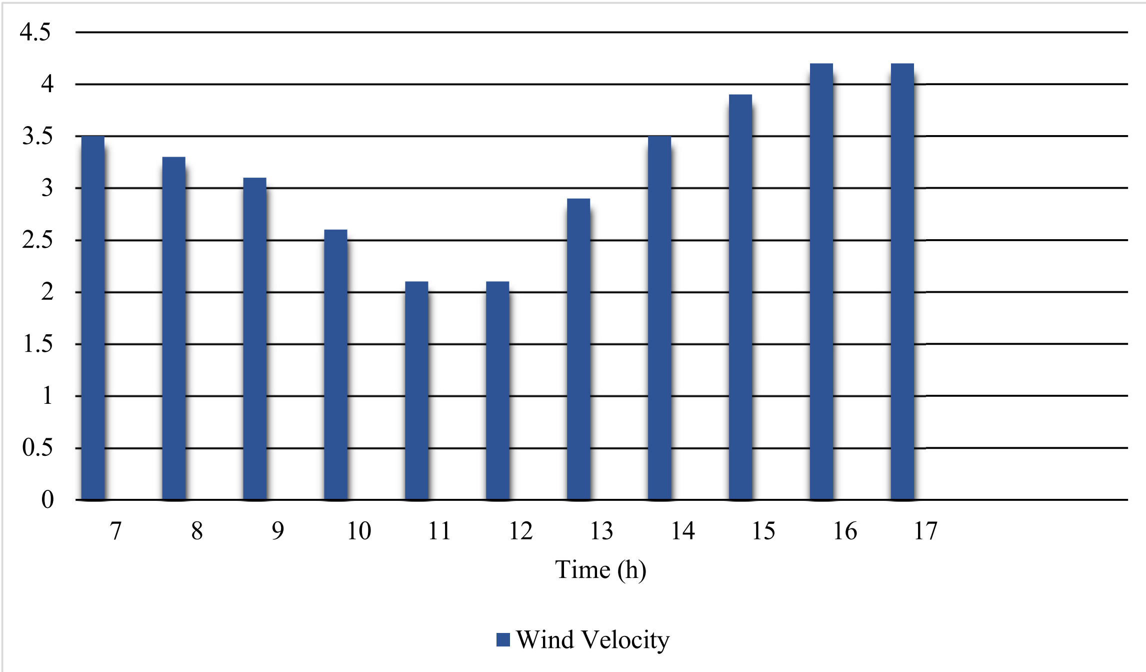
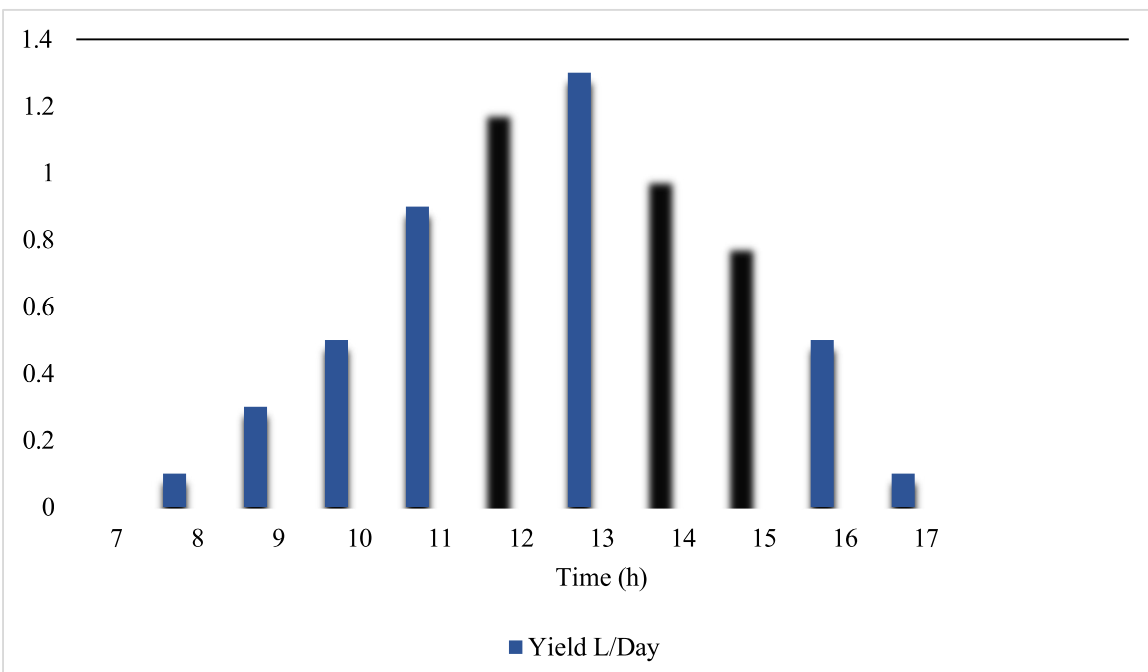


Figure 5. Wind Velocity of 1 Feb 2024



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Volume 06 Issue 2
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ISSN:1624-1940
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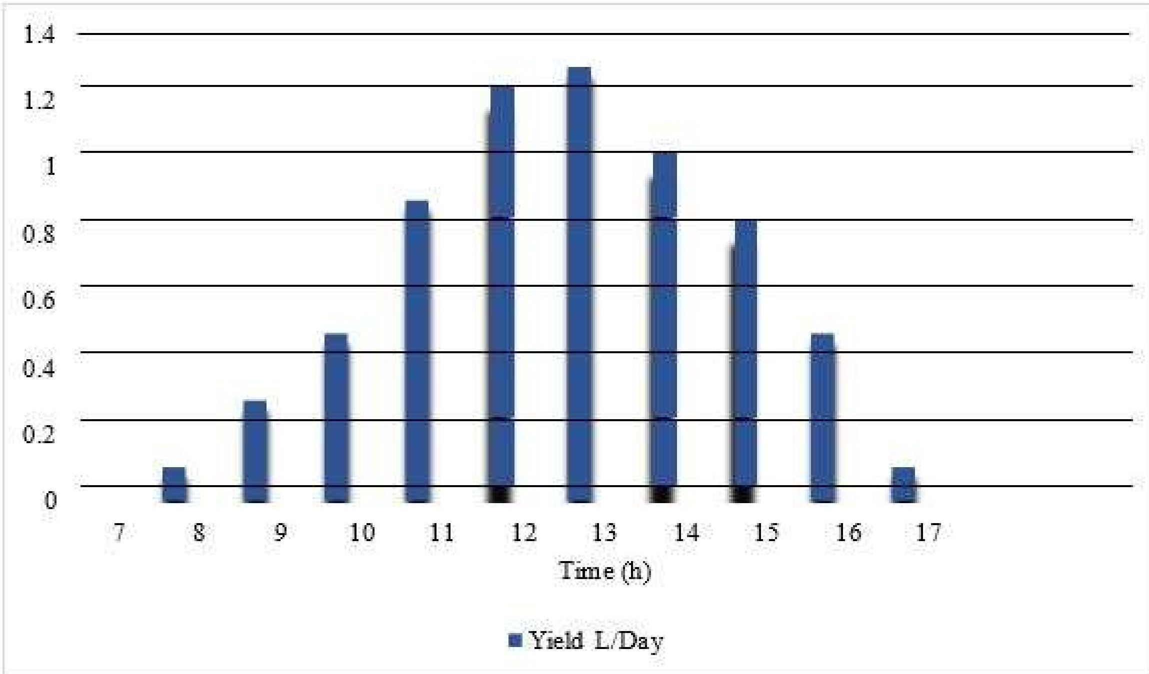

Figure 6. Yield L/Day of 1 Feb 2024

Conclusion:
The compact solar still standalone system represents a significant advancement in sustainable water purification technology. Its efficient design, cost-effectiveness, and environmental benefits make it a promising solution to address global water scarcity. By continuing to optimize and refine the system, this research contributes to the broader goal of providing accessible and sustainable clean water solutions for communities worldwide.
Future Directions
While the compact solar still system has shown promising results, further research and development are needed to enhance its scalability, durability, and integration with other renewable energy systems. Future work should focus on:

1. **Scaling Up:**
Developing larger-scale models to meet the water purification needs of communities and agricultural applications.

2. **Energy Storage Integration:**
Exploring the integration of renewable energy storage solutions, such as photovoltaic-thermal (PVT) systems, to ensure continuous operation during low solar intensity periods.

3. **Long-Term Durability:**
Assessing the long-term durability and maintenance requirements of the system in various environmental conditions to ensure sustained performance.

4. **Community Deployment:**
Implementing pilot projects in remote and off-grid communities to evaluate the system's practical applicability and gather user feedback for further improvements.

ISSN:1624-1940
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Acknowledgments
We would like to thank Dr. Atul A Sagade for his invaluable assistance with the statistical analysis. His knowledge and guidance knowingly contributed to the success of this research.

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