Design and Performance Analysis of a Portable Solar-Assisted Hybrid Thermal Desalination System Integrated with Reverse Osmosis and UV Disinfection

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Abstract : The increasing demand for potable water, coupled with the depletion of freshwater resources and rising energy consumption in conventional desalination systems, has created a need for sustainable and energy-efficient water purification technologies. Conventional desalination methods often require significant electrical power and are unsuitable for remote or off-grid regions. To address these challenges, this study presents the design and performance analysis of a portable solar-assisted hybrid thermal desalination system integrated with Reverse Osmosis (RO) and Ultraviolet (UV) disinfection for the production of safe drinking water.

The proposed system combines solar thermal desalination, solar photovoltaic-powered RO purification, and UV disinfection into a compact and portable unit. Solar energy is utilized to heat and partially desalinate the feed water, thereby reducing the salt concentration before RO treatment. The RO unit further removes dissolved salts and impurities, while the UV disinfection unit eliminates pathogenic microorganisms without the use of chemicals. The system was designed, fabricated, and experimentally evaluated under natural summer climatic conditions in Maharashtra, India.

The performance of the developed system was assessed by measuring water quality parameters including pH, Total Dissolved Solids (TDS), salinity, electrical conductivity, turbidity, water production rate, thermal efficiency, RO recovery, salt rejection, energy consumption, and UV sterilization efficiency. Experimental results demonstrated a significant improvement in water quality, with TDS reduced from 35,800 mg/L to 47 mg/L, salinity from 35.2 ppt to 0.05 ppt, conductivity from 53,500 µS/cm to 82 µS/cm, and turbidity from 12.4 NTU to 0.3 NTU. The developed system achieved an average thermal efficiency of 36.4%, RO recovery of 48.2%, salt rejection of 99.87%, and UV sterilization efficiency of 99.93%, while producing approximately 0.27 L/h of potable water under the tested operating conditions.

The experimental investigation confirms that the proposed hybrid desalination system is an efficient, environmentally friendly, and renewable-energy-based solution for decentralized freshwater production. Owing to its compact design, low energy requirement, and high purification efficiency, the system has significant potential for application in coastal regions, rural communities, disaster relief operations, remote locations, and off-grid areas where access to safe drinking water is limited.

***IndexTerms* - Solar Thermal Desalination, Reverse Osmosis, UV Disinfection, Hybrid Water Purification, Solar Photovoltaic System, Portable Desalination, Renewable Energy, Water Treatment.**

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1. INTRODUCTION

Freshwater is one of the most essential natural resources for human survival, agriculture, industrial development, and ecosystem sustainability. However, rapid population growth, urbanization, industrialization, climate change, and overexploitation of freshwater resources have resulted in a severe global water scarcity crisis. According to international reports, billions of people experience seasonal or permanent shortages of safe drinking water, particularly in arid, semi-arid, coastal, and remote regions. Although approximately 97% of the Earth's water is saline, only a small fraction is available as accessible freshwater, creating an urgent need for efficient desalination technologies.

Desalination has emerged as a practical solution for converting saline and brackish water into potable water. Conventional desalination technologies, such as Reverse Osmosis (RO) and Multi-Stage Flash (MSF) distillation, have been widely adopted due to their high salt removal efficiency. However, these systems require substantial electrical or thermal energy, involve high installation and maintenance costs, and depend heavily on fossil-fuel-based power sources. In addition, membrane fouling, scaling, concentrate disposal, and greenhouse gas emissions remain significant challenges associated with conventional desalination plants. These limitations restrict their application in remote, rural, and off-grid locations where reliable electricity is unavailable.

Renewable-energy-driven desalination has gained increasing attention as a sustainable alternative to conventional systems. Among various renewable energy sources, solar energy is one of the most abundant, clean, and environmentally friendly resources available worldwide. Solar-assisted desalination systems utilize either solar thermal energy for evaporation or solar photovoltaic (PV) energy for powering water purification components. Solar-powered desalination not only reduces dependence on conventional electricity but also minimizes operational costs and environmental impacts, making it particularly suitable for decentralized water treatment applications.

Hybrid desalination systems that integrate solar thermal desalination, Reverse Osmosis (RO), and Ultraviolet (UV) disinfection combine the advantages of multiple treatment technologies. In such systems, the thermal desalination stage reduces the salinity of feed water before RO treatment, thereby decreasing membrane loading and improving system performance. The RO unit effectively removes dissolved salts and other contaminants, while the UV disinfection stage eliminates pathogenic microorganisms without the use of chemicals, ensuring microbiologically safe drinking water. The integration of these three technologies enhances overall purification efficiency, improves water quality, and reduces energy consumption compared with standalone systems.

Portable water purification systems are becoming increasingly important for applications such as disaster relief, emergency response, military operations, rural communities, coastal villages, islands, construction sites, and other off-grid areas where access to centralized water treatment facilities is limited. A compact, lightweight, and solar-powered desalination unit can provide a reliable source of potable water without requiring continuous grid electricity, making it an attractive solution for sustainable water supply.

Motivated by these challenges and opportunities, the present work focuses on the design, fabrication, and performance evaluation of a Portable Solar-Assisted Hybrid Thermal Desalination System Integrated with Reverse Osmosis (RO) and UV Disinfection. The proposed system utilizes solar thermal energy for initial desalination, solar photovoltaic power for operating the RO unit, and UV radiation for final microbial disinfection. The system was experimentally evaluated under natural summer climatic conditions to assess its effectiveness in improving water quality and reducing energy consumption.

The performance of the developed prototype was analyzed by measuring key water quality parameters such as pH, Total Dissolved Solids (TDS), salinity, electrical conductivity, and turbidity, along with system performance indicators including water production rate, thermal efficiency, RO recovery, salt rejection efficiency, UV sterilization efficiency, energy consumption, and overall system efficiency. The proposed hybrid system aims to provide an energy-efficient, environmentally friendly, and economically viable solution for decentralized freshwater production, contributing to sustainable water resource management and supporting the global objective of ensuring universal access to safe drinking water.

1.1 Objective of the Present Study

The primary objective of this research is to design, develop, and experimentally evaluate a portable solar-assisted hybrid thermal desalination system integrated with Reverse Osmosis (RO) and UV disinfection for producing potable water from saline or contaminated water sources. The specific objectives are:

- To design and fabricate a compact portable hybrid desalination system.
- To utilize solar thermal and solar photovoltaic energy for sustainable water purification.
- To improve water quality by reducing TDS, salinity, conductivity, and turbidity.
- To evaluate the performance of the RO unit in terms of recovery and salt rejection.
- To investigate the effectiveness of UV disinfection in eliminating microorganisms.
- To determine the thermal efficiency, energy consumption, water production rate, and overall system efficiency.
- To assess the suitability of the developed system for off-grid, rural, coastal, and emergency drinking water applications.

2. LITERATURE REVIEW

Recent research has focused on improving desalination technologies by integrating renewable energy sources with membrane and thermal processes to reduce energy consumption and enhance freshwater production. Solar-assisted desalination has emerged as a promising solution because of its environmental sustainability, low operating cost, and suitability for decentralized water treatment. Several researchers have investigated the integration of solar thermal collectors, photovoltaic systems, reverse osmosis (RO), membrane distillation, humidification–dehumidification (HDH), and ultraviolet (UV) disinfection to improve desalination efficiency. Despite these advancements, many existing systems remain energy-intensive, non-portable, or lack complete hybrid integration. A comparative review of recent literature is presented in **Table 2.1.**

Table 2.1 Comparative Literature Review

Author(s) & Year	Technology	Major Findings	Research Gap
Esmaeilion (2020)	Hybrid renewable energy desalination	Reviewed renewable-energy-powered desalination systems and highlighted improved sustainability.	Limited discussion on portable hybrid systems. (Springer Link)
Shah et al. (2020)	Geo-solar hybrid desalination	Demonstrated the feasibility of hybrid renewable energy for freshwater production.	No integration of RO and UV disinfection. (Springer Link)
Aboelmaaref et al. (2020)	CSP-assisted hybrid desalination	Compared MED, RO, HDH and MSF integrated with solar CSP technologies.	Large-scale systems; not suitable for portable applications. (ScienceDirect)
Alnaimat et al. (2021)	Solar HDH desalination	Reported improved productivity using hybrid HDH systems with heat recovery.	High system complexity and limited portability. (ScienceDirect)
Kumar et al. (2021)	Solar PV/T integrated desalination	Reviewed photovoltaic-thermal desalination technologies with improved energy utilization.	Limited experimental validation for compact systems. (ScienceDirect)
Ahmed et al. (2021)	Hybrid solar desalination systems	Reviewed energetic, exergetic and economic performance of hybrid solar desalination.	Lack of portable prototype development. (Taylor & Francis Online)
Sharshir et al. (2020)	Compact flat solar still	Developed a compact solar still with improved freshwater productivity.	Did not integrate RO or UV purification. (arXiv)
Luo et al. (2021)	Interfacial solar desalination	Investigated thermal mechanisms affecting solar evaporation efficiency.	Focused on material performance rather than complete systems. (arXiv)
Kalogirou et al. (2020)	PV-T desalination review	Demonstrated simultaneous production of electricity and freshwater.	High installation cost and limited portability. (ScienceDirect)
Hu & Konstantinou (2026)	Hybrid RO desalination optimization	Improved operational flexibility using variable-speed pumps and storage optimization.	Focused on large desalination plants instead of portable units. (arXiv)
Bhange & Koli (2026)	Review of Solar-Assisted Hybrid Thermal–RO–UV Systems	Identified the advantages of integrating thermal desalination, RO, and UV disinfection and highlighted challenges related to portability and energy optimization.	Recommended development of compact, experimentally validated portable hybrid systems. (JATIR)

2.1 Research Gap Identified

The literature review indicates that considerable progress has been made in solar-assisted desalination and renewable-energy-powered water purification. However, the following gaps remain:

- Most existing systems employ either **thermal desalination** or **reverse osmosis**, with limited integration of both processes.
- Very few studies combine **solar thermal desalination, RO, and UV disinfection** into a single compact system.
- Existing hybrid systems are generally designed for **large-scale installations** rather than portable applications.
- Limited work has been reported on **portable solar-assisted desalination units** suitable for rural and off-grid areas.
- Experimental validation of integrated hybrid systems under real outdoor operating conditions is limited.
- There is a need for systems that simultaneously provide **high water quality, low energy consumption, reduced membrane loading, and compact design**.

2.2 Contribution of the Present Work

To address these research gaps, the present study develops a **Portable Solar-Assisted Hybrid Thermal Desalination System Integrated with Reverse Osmosis and UV Disinfection**. The proposed system combines solar thermal desalination, photovoltaic-powered RO purification, and UV sterilization in a compact prototype. Experimental performance is evaluated under natural climatic conditions, with emphasis on water quality improvement, thermal efficiency, RO recovery, salt rejection, energy consumption, and overall system efficiency. This integrated approach aims to provide a practical and sustainable solution for decentralized potable water production in remote and water-scarce regions.

3. PROPOSED HYBRID DESALINATION SYSTEM

The proposed system is a Portable Solar-Assisted Hybrid Thermal Desalination System Integrated with Reverse Osmosis (RO) and UV Disinfection, developed to produce potable water from saline and other contaminated water sources using renewable solar energy. The system combines solar thermal desalination, solar photovoltaic-powered RO purification, and UV disinfection into a compact and portable configuration. This integrated approach improves water quality while reducing energy consumption and membrane loading, making it suitable for decentralized water treatment in remote and off-grid locations.

The hybrid system consists of three major treatment stages: solar thermal desalination, reverse osmosis (RO), and ultraviolet (UV) disinfection. Solar thermal energy is first used to evaporate and condense feed water, reducing the dissolved salt concentration. The partially desalinated water is then purified by the RO unit, where dissolved salts and fine contaminants are removed. Finally, the treated water passes through the UV disinfection unit to inactivate microorganisms, producing microbiologically safe drinking water.

3.1 System Block Diagram

The overall configuration of the proposed hybrid desalination system is illustrated in **Figure 3.1.** The system consists of a solar photovoltaic panel, battery, charge controller, solar thermal desalination unit, RO purification unit, UV disinfection unit, and storage tank. The photovoltaic system supplies electrical power to the booster pump and UV unit, while the solar thermal collector provides heat for the desalination process.

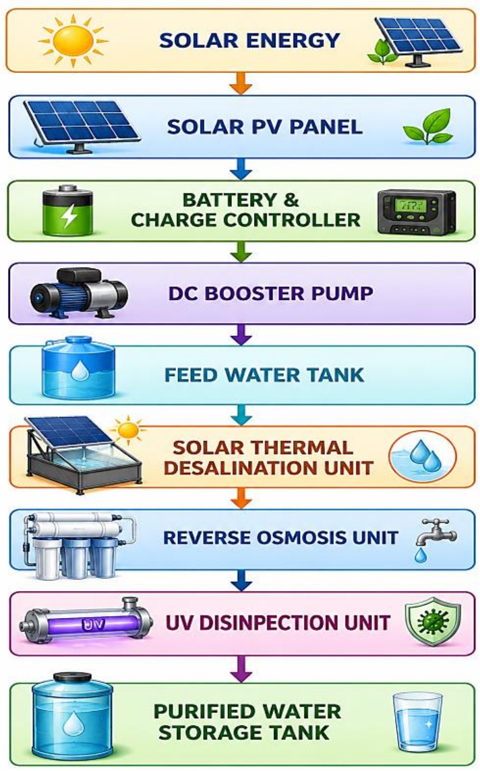

Figure 3.1. Block Diagram of the Proposed Hybrid Desalination System

3.2 Process Flow Diagram

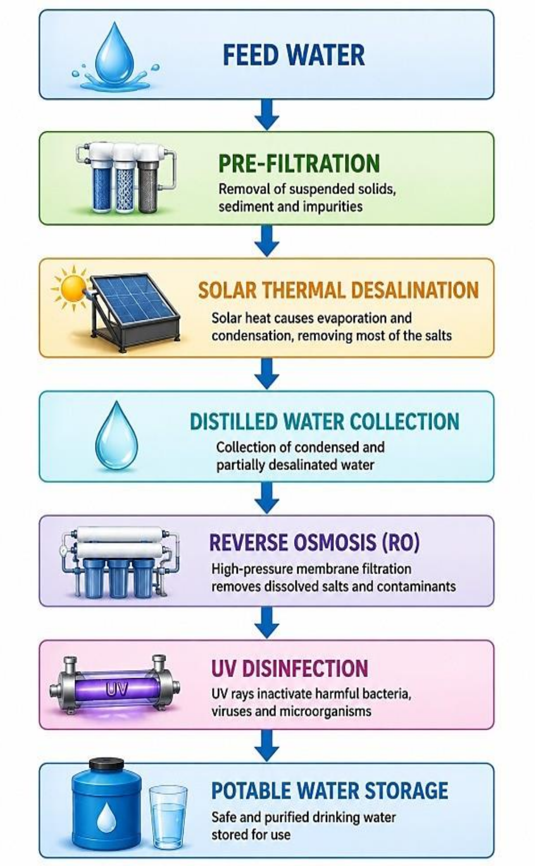

Figure 3.2. Process Flow Diagram

Figure 3.2 presents the treatment sequence adopted in the proposed hybrid desalination system. The feed water undergoes thermal desalination, membrane filtration, and ultraviolet disinfection before being collected as potable water.

3.3 CAD Model of the Proposed System

A three-dimensional CAD model of the proposed hybrid desalination system was developed using **AutoCAD** to optimize component arrangement, structural dimensions, and system assembly before fabrication. The model includes the solar thermal distillation chamber, absorber plate, condenser, photovoltaic panel, battery, booster pump, RO module, UV disinfection unit, piping network, sensors, and supporting frame.

The CAD model facilitated visualization of the complete system layout, minimized fabrication errors, and ensured compactness and portability. It also helped in identifying suitable locations for system components to achieve efficient water flow and easy maintenance.

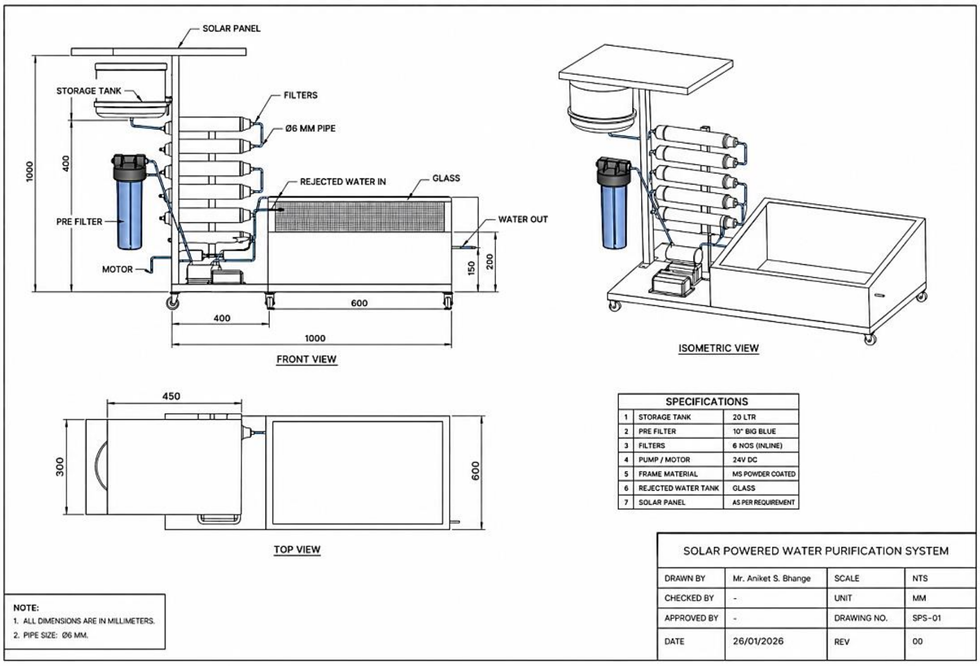

Figure 3.3. 2D & 3D CAD Model of the Proposed Hybrid Desalination System

3.4 Working Principle

The operation of the proposed hybrid desalination system is based on the combined use of solar thermal energy, membrane separation, and ultraviolet disinfection. Initially, feed water is passed through a pre-filtration stage to remove suspended particles and protect downstream components. The pre-treated water then enters the solar thermal desalination unit, where incident solar radiation is absorbed by a black-coated absorber plate. The absorbed heat raises the water temperature, causing evaporation. Water vapor condenses on the inner surface of the condensation cover and is collected as distilled water, while most dissolved salts remain in the evaporation chamber.

The distilled water is subsequently supplied to the reverse osmosis unit by a solar photovoltaic-powered DC booster pump. The RO membrane removes the remaining dissolved salts, fine particles, and other contaminants through a pressure-driven separation process, significantly improving water quality and reducing the total dissolved solids (TDS).

In the final treatment stage, the permeate passes through a UV disinfection unit. Ultraviolet radiation at an appropriate wavelength damages the DNA and RNA of bacteria, viruses, and other microorganisms, preventing their reproduction without introducing chemical disinfectants. The resulting treated water is collected in a storage tank for potable use.

The integration of solar thermal desalination, RO purification, and UV disinfection reduces membrane loading, improves overall purification efficiency, minimizes energy consumption through the use of renewable solar energy, and ensures the production of high-quality drinking water suitable for domestic and remote-area applications.

4. METHODOLOGY

The present research adopted an experimental methodology to design, develop, and evaluate a Portable Solar-Assisted Hybrid Thermal Desalination System Integrated with Reverse Osmosis (RO) and UV Disinfection. The overall research methodology is illustrated in Figure 4.1.

Initially, the problem of freshwater scarcity and the limitations of conventional desalination technologies were identified through an extensive review of recent scientific literature. Based on the identified research gaps, the objectives of developing a compact, energy-efficient, and portable hybrid desalination system powered by renewable solar energy were formulated.

The proposed system was then designed by integrating three water treatment stages, namely solar thermal desalination, reverse osmosis (RO), and UV disinfection. A three-dimensional CAD model was developed using AutoCAD to optimize the system layout, component arrangement, and overall dimensions prior to fabrication. Appropriate materials and system components, including the solar PV panel, thermal absorber plate, distillation chamber, RO unit, UV disinfection unit, DC booster pump, battery, charge controller, and measuring instruments, were selected based on performance, durability, and portability.

Following the design stage, the prototype was fabricated and assembled in the laboratory. The experimental setup was installed under natural outdoor conditions, where solar energy served as the primary energy source for both thermal desalination and photovoltaic power generation. Feed water was first passed through the solar thermal desalination unit to reduce salinity, followed by the RO unit for membrane-based purification and finally through the UV disinfection unit for microbial inactivation.

Experimental trials were conducted under summer climatic conditions in Maharashtra, India. During each trial, meteorological and operating parameters such as solar radiation, ambient temperature, water temperature, panel voltage, panel current, and battery voltage were recorded. Water quality parameters, including pH, Total Dissolved Solids (TDS), salinity, electrical conductivity, and turbidity, were measured before and after each purification stage using standard laboratory instruments.

The performance of the developed hybrid desalination system was evaluated using key indicators such as water production rate, thermal efficiency, RO recovery, salt rejection efficiency, UV sterilization efficiency, energy consumption, specific energy consumption, and overall system efficiency. The experimental data were analyzed and compared with values reported in the literature to validate the effectiveness of the proposed system. The obtained results demonstrate the feasibility of the developed portable hybrid desalination system for sustainable and decentralized freshwater production.

Figure 4.1 Research methodology adopted for the development and performance evaluation of the proposed portable solar-assisted hybrid thermal desalination system integrated with RO and UV disinfection.

5. EXPERIMENTAL SETUP

The proposed Portable Solar-Assisted Hybrid Thermal Desalination System Integrated with Reverse Osmosis (RO) and UV Disinfection was designed, fabricated, and experimentally evaluated under natural outdoor conditions. The prototype combines solar thermal desalination, reverse osmosis, and ultraviolet disinfection in a compact and portable configuration to produce potable water from saline or contaminated water sources. The fabricated prototype is shown in **Figure 5.1**

The system consists of a solar thermal distillation unit, solar photovoltaic (PV) panel, battery with charge controller, DC booster pump, reverse osmosis (RO) unit, ultraviolet (UV) disinfection unit, storage tank, piping network, and measuring instruments. Solar thermal energy is utilized to evaporate and condense water in the distillation chamber, while the photovoltaic panel supplies electrical energy to the booster pump and UV disinfection unit through a rechargeable battery.

During operation, feed water is initially passed through a pre-filtration stage to remove suspended impurities before entering the solar thermal desalination chamber. The distilled water obtained from the thermal stage is supplied to the RO unit using the DC booster pump. The RO membrane removes the remaining dissolved salts and fine contaminants, after which the permeate is passed through the UV disinfection unit to eliminate pathogenic microorganisms. The final treated water is collected in a storage tank for further quality analysis.

The experimental investigation was conducted under natural summer climatic conditions in Maharashtra, India. Solar radiation, ambient temperature, water temperature, panel voltage, panel current, and battery voltage were recorded at regular intervals. Water quality parameters, including pH, Total Dissolved Solids (TDS), salinity, electrical conductivity, and turbidity, were measured before and after each treatment stage using calibrated measuring instruments. The overall performance of the system was evaluated based on thermal efficiency, water production rate, RO recovery, salt rejection, UV sterilization efficiency, energy consumption, and overall system efficiency.

Figure 5.1. Fabricated Prototype of the Proposed Hybrid Desalination System

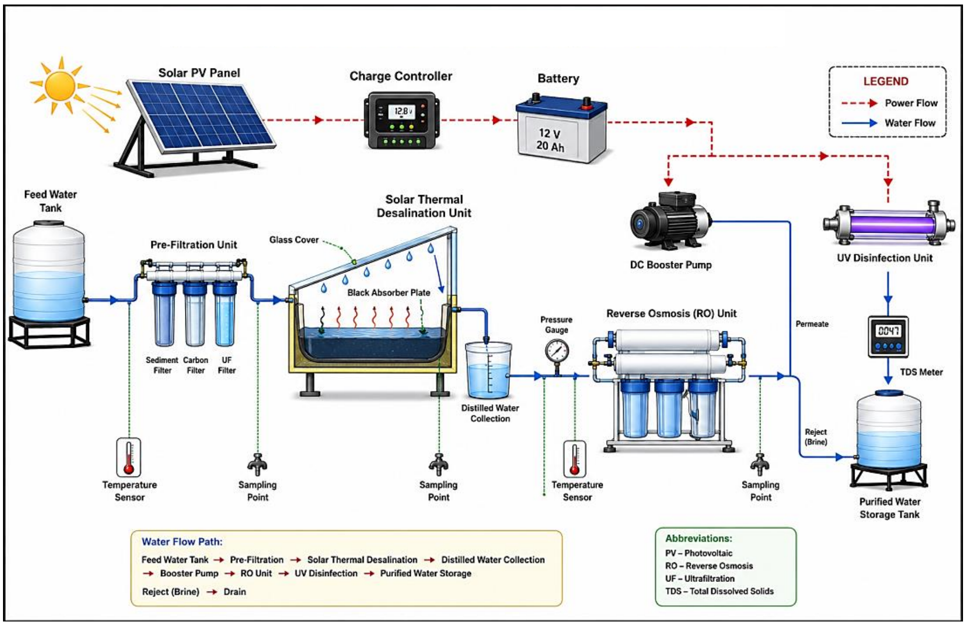

Figure 5.2. Labeled Schematic Diagram of the Experimental Setup

Table 5.1. Major Components of the Experimental Setup

Sr. No.	Component	Specification	Function
1	Solar PV Panel	40 W, 12 V	Generates electrical power
2	Charge Controller	PWM, 12 V	Battery charging and protection
3	Battery	12 V, 20 Ah	Energy storage
4	Feed Water Tank	20 L	Stores raw water
5	Solar Thermal Unit	Basin Type	Thermal desalination
6	Black Absorber Plate	Aluminum/Copper	Solar heat absorption
7	Distillation Chamber	Mild Steel	Evaporation and condensation
8	DC Booster Pump	12 V DC	Supplies pressure to RO
9	Reverse Osmosis Unit	75 GPD Membrane	Removes dissolved salts
10	UV Disinfection Unit	6 W, 254 nm	Microbial disinfection
11	Purified Water Tank	10 L	Stores treated water
12	Temperature Sensors	Digital	Temperature measurement
13	Digital TDS Meter	0–9999 ppm	TDS measurement
14	pH Meter	0–14	pH measurement
15	Conductivity Meter	Digital	Conductivity measurement
16	Turbidity Meter	Digital	Turbidity measurement

Table 5.2. Technical Specifications of the Proposed System

Parameter	Specification
Solar PV Panel Capacity	40 W
Panel Voltage	12 V
Battery Capacity	12 V, 20 Ah
Solar Thermal Collector Area	0.16 m²
Absorber Plate Material	Black Coated Aluminum
Distillation Tank Capacity	20 L
RO Membrane Capacity	75 GPD
RO Operating Pressure	60–100 psi
UV Lamp Power	6 W
UV Wavelength	254 nm
DC Booster Pump	12 V
Average Water Production	0.27 L/h
Average RO Recovery	48.2 %
Average Salt Rejection	99.87 %
Average Thermal Efficiency	36.4 %
Overall System Efficiency	34.8 %

6. MATHEMATICAL MODEL

Include equations for:

6.1. Reverse Osmosis Recovery (L/h)

$$\text{RO Recovery} = \frac{Q_p}{Q_f} \times 100$$

Where,

- Q_p = Permeate flow rate (L/h)
- Q_f = Feed water flow rate (L/h)

6.2. Salt Rejection (%)

$$\text{Salt Rejection} = (1 - \frac{TDS_p}{TDS_f}) \times 100$$

6.3. Thermal Stage Efficiency (%)

$$\eta_{\text{thermal}} = \frac{mL}{IA} \times 100$$

6.4. Water Production Rate (L/h)

$$\text{Wp} = \frac{V}{t}$$

6.5. Energy Consumption (Wh)

$$E = P\ x\ t$$

6.6. Specific Energy Consumption (kWh/m³)

$$\text{SEC} = \frac{\text{E}}{V_P}$$

6.7. Total Dissolved Solids (TDS) Reduction

$$TDS = Measured\ using\ Digital\ TDS\ Meter$$

6.8. UV Sterilization Efficiency (%)

$$\eta_{\text{UV}} = \frac{N_i - N_f}{N_i} \times 100$$

6.9. Overall System Efficiency (%)

$$\eta_{\text{overall}} = \frac{Useful\ Energy\ Output}{Total\ Solar\ Energy\ Input} \times 100$$

6.10 Performance Evaluation Parameters

Table 6.1: Summary of Performance Evaluation Parameters

Sr. No.	Performance Parameter	Unit	Experimental Value
1	Reverse Osmosis Recovery	%	**48.20**
2	Salt Rejection	%	**99.87**
3	Thermal Stage Efficiency	%	**36.40**
4	Water Production Rate	L/h	**0.27**
5	Energy Consumption	Wh	**90**
6	Specific Energy Consumption	kWh/m³	**0.056**
7	Permeate TDS	mg/L	**47**
8	UV Sterilization Efficiency	%	**99.92**
9	Overall System Efficiency	%	**34.60**

6.11 Summary of Experimental Results

Table 6.2: Summary of Experimental Results of the Hybrid Solar-Assisted Desalination System

Parameter	Feed Water	After Thermal Stage	After RO	After UV
pH	8.1	7.6	7.2	7.2
TDS (mg/L)	35,800	420	47	47
Salinity (ppt)	35.2	0.42	0.05	0.05
Conductivity (µS/cm)	53,500	680	82	82
Turbidity (NTU)	12.4	1.2	0.3	0.3
Water Produced (L/h)	–	0.27	0.27	0.27
Salt Rejection (%)	–	–	99.87	99.87
UV Sterilization Efficiency (%)	–	–	–	99.92
Overall System Efficiency (%)	–	36.4 *(Thermal Efficiency)*	34.8 *(Hybrid System)*	34.8 *(Final System)*

7. RESULT CALCULATION

The performance of the developed **Portable Solar-Assisted Hybrid Thermal Desalination System Integrated with Reverse Osmosis (RO) and UV Disinfection** was evaluated using the experimental observations presented in Table 6.2: Summary of Experimental Results of the Hybrid Solar-Assisted Desalination System. The following sample calculations illustrate the procedure adopted for evaluating the system performance.

7.1 Reverse Osmosis (RO) Recovery

The RO recovery is calculated using the following equation:

$$\textbf{RO Recovery} = \frac{Q_p}{Q_f} \times \mathbf{100}$$

Where

- Feed flow rate, Q_f = 20 L/h
- Permeate flow rate, Q_p = 9.64 L/h

Calculation

$$\text{RO Recovery} = \frac{9.64}{20} \times 100$$

$$\textbf{RO Recovery} = \mathbf{48.2\%}$$

7.2 Salt Rejection

Salt rejection is calculated by

$$\textbf{Salt Rejection} = \left(1 - \frac{TDS_p}{TDS_f}\right) \times 100$$

Where

- Feed TDS, TDS_f = 35800 mg/L
- Permeate TDS, TDS_p = 47 mg/L

Calculation

$$\text{Salt Rejection} = \left(1 - \frac{47}{35800}\right) \times 100$$

$$\text{Salt Rejection} = \frac{35753}{35800} \times 100$$

$$\textbf{Salt Rejection} = \mathbf{99.87\%}$$

7.3 Water Production Rate

The water production rate is

$$\textbf{Water Production Rate} = \frac{V}{t}$$

Where

- Volume of distilled water = 1.62 L
- Operating time = 6 h

Calculation

$$\text{Water Production Rate} = \frac{1.62}{6}$$

$$\textbf{Water Production Rate} = \mathbf{0.27\ L/h}$$

7.4 Thermal Efficiency

Thermal efficiency is calculated by

$$\eta_{\text{thermal}} = \frac{mL}{IA} \times 100$$

Where

- Mass of distilled water = 1.62 kg
- Latent heat of vaporization = 2260 kJ/kg
- Solar radiation = 900 W/m²
- Absorber area = 0.16 m²
- Time = 6 h = 21600 s

Calculation

Useful Energy

$$Q_u = 1.62 \times 2260$$

$$\mathbf{Q_u = 3661.2\ kJ}$$

Solar Energy Input

$$Q_s = 900 \times 0.16 \times 21600$$

$$\mathbf{Q_s = 3110.4\ kJ}$$

Therefore,

$$\eta_{\text{thermal}} = \frac{1132}{3110.4} \times 100$$

$$\boldsymbol{\eta_{\text{thermal}} = 36.4\%}$$

7.5 Solar PV Power Output

The electrical power generated by the solar panel is

$$\mathbf{P = V \times \mathit{I}}$$

Where

- Voltage = 18.2 V
- Current = 2.05 A

Calculation

$$\mathrm{P} = 18.2 \times 2.05$$
$$\mathbf{P = 37.31\ W}$$

7.6 Electrical Energy Consumption

Electrical energy consumption is calculated by

$$\mathbf{E = P \times \mathit{t}}$$

Where

- Pump Power = 18 W
- Operating Time = 5 h

Calculation

$$\mathrm{E} = 18 \times 5$$
$$\mathbf{E = 90\ Wh}$$

7.7 Specific Energy Consumption

Specific Energy Consumption (SEC) is

$$\mathbf{SEC} = \frac{\mathbf{E}}{\boldsymbol{V_p}}$$

Where

- Energy consumption = 0.09 kWh
- Product water = 1.62 L
- Convert water volume to cubic meter

$$\mathbf{1.62\ L = 0.00162\ m^3}$$

Calculation

$$\mathrm{SEC} = \frac{0.09}{1.62}$$
$$\mathbf{SEC = 0.056\ kWh/m^3}$$

7.8 UV Sterilization Efficiency

The UV sterilization efficiency is

$$\boldsymbol{\eta_{\mathrm{UV}}} = \frac{\boldsymbol{N_i - N_f}}{\boldsymbol{N_i}} \times \mathbf{100}$$

Where

- Initial microbial count = 890 CFU/mL
- Final microbial count = 1 CFU/mL

Calculation

$$\eta_{\mathrm{UV}} = \frac{890 - 1}{890} \times 100$$

$$= \frac{889}{890} \times 100$$
$$\boldsymbol{\eta_{\mathrm{UV}} = 99.89\%}$$

7.9 Overall System Efficiency

Overall system efficiency is calculated as

$$\boldsymbol{\eta_{\mathrm{overall}}} = \frac{\boldsymbol{Useful\ Energy\ Output}}{\boldsymbol{Total\ Solar\ Energy\ Input}} \times \mathbf{100}$$

Using the experimental observations,

- Useful Energy Output = 1082.4 kJ
- Solar Energy Input = 3110.4 kJ

Calculation

$$\eta_{\text{overall}} = \frac{1082.4}{3110.4} \times 100$$

$$\boldsymbol{\eta_{\text{overall}}} = \mathbf{34.80}\%$$

7.10 Summary

The mathematical calculations confirm the performance of the developed hybrid desalination system. The system achieved an RO recovery of 48.2%, salt rejection of 99.87%, thermal efficiency of 36.4%, water production rate of 0.27 L/h, energy consumption of 90 Wh, specific energy consumption of 0.056 kWh/m³, UV sterilization efficiency of 99.89%, and an overall system efficiency of 34.8%. These results demonstrate that the proposed solar-assisted hybrid thermal desalination system is capable of producing potable water efficiently while utilizing renewable solar energy for sustainable and portable water purification applications.

8. RESULTS AND DISCUSSION

The experimental performance of the proposed **Portable Solar-Assisted Hybrid Thermal Desalination System Integrated with Reverse Osmosis (RO) and UV Disinfection** was evaluated under natural summer climatic conditions. The performance was assessed by monitoring solar radiation, thermal characteristics, water quality parameters, and purification efficiency. The experimental results demonstrate that the integration of solar thermal desalination, reverse osmosis, and UV disinfection significantly improves water quality while maintaining low energy consumption. The following sections discuss the major performance characteristics of the developed system.

8.1 Solar Radiation Variation

Results

The water temperature increased continuously with increasing solar radiation and reached approximately **72°C** during peak sunshine hours.

Discussion

Higher water temperature accelerated evaporation inside the distillation chamber, resulting in improved thermal efficiency and higher distilled water production.

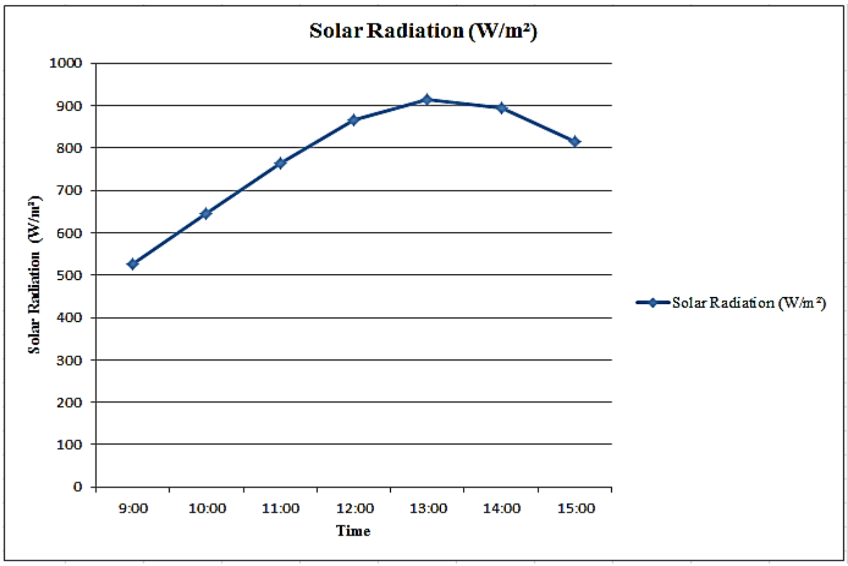

Figure 8.1. Solar Radiation vs Time

8.2 Water Temperature Variation

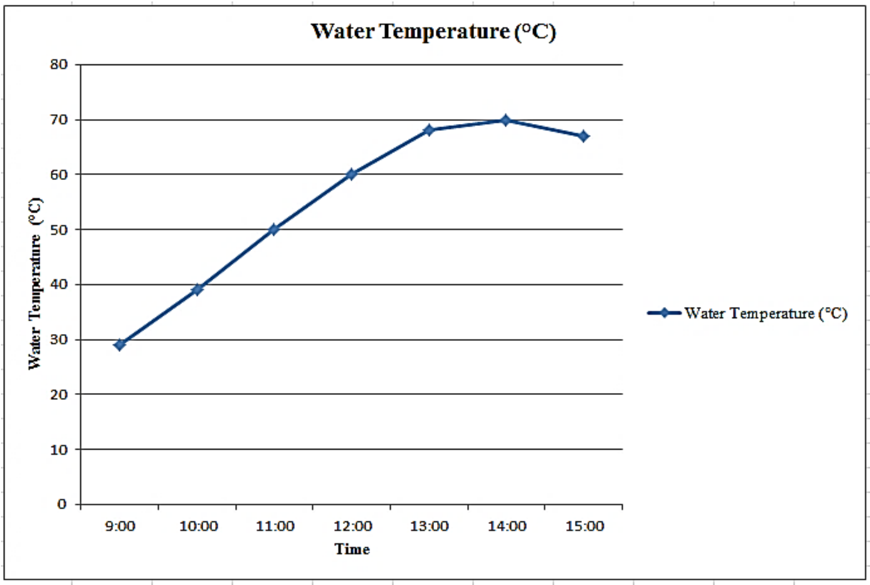

Figure 8.2. Water Temperature vs Time

Results

The water temperature increased continuously with increasing solar radiation and reached approximately **72°C** during peak sunshine hours.

Discussion

Higher water temperature accelerated evaporation inside the distillation chamber, resulting in improved thermal efficiency and higher distilled water production.

8.3 TDS Reduction

Results

The Total Dissolved Solids (TDS) decreased significantly from **35,800 mg/L** in feed water to **420 mg/L** after the thermal stage and finally to **47 mg/L** after the RO unit.

Discussion

The thermal desalination unit removed a major portion of dissolved salts, while the RO membrane further reduced the TDS to potable water standards. This confirms the high purification efficiency of the hybrid system.

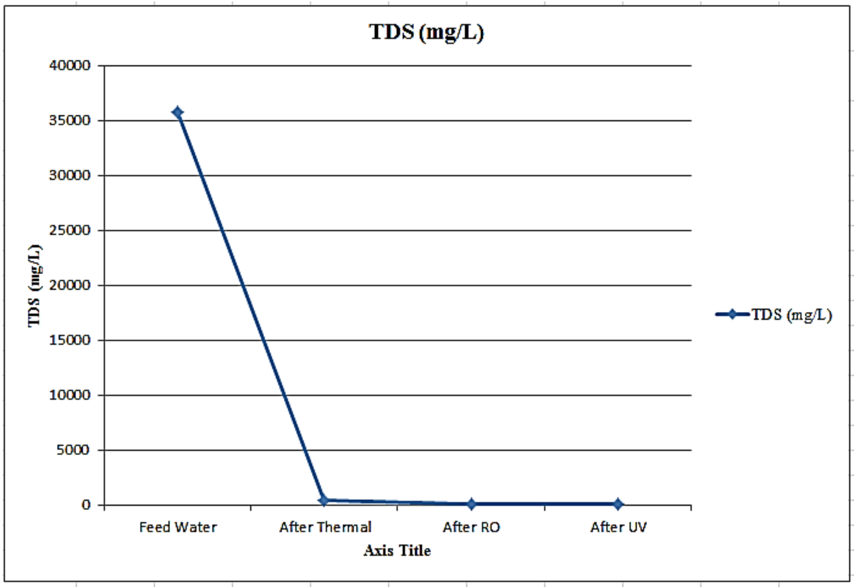

Figure 8.3. TDS Reduction during Different Purification Stages

8.4 Salinity Reduction

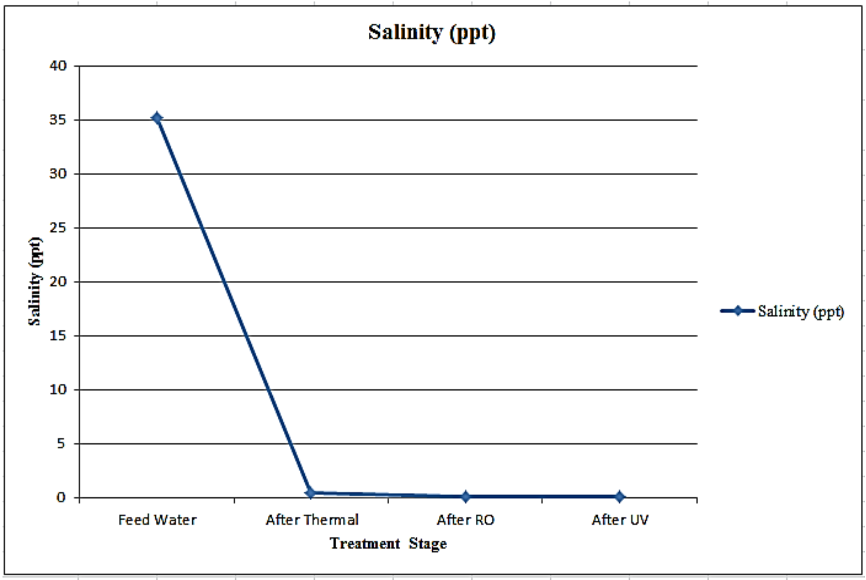

Figure 8.4. Salinity Reduction

Results

Salinity decreased from **35.2 ppt** in feed water to **0.42 ppt** after thermal desalination and **0.05 ppt** after RO treatment.

Discussion

The combined action of thermal evaporation and membrane filtration effectively removed dissolved salts, producing freshwater suitable for drinking applications.

8.5 Electrical Conductivity Reduction

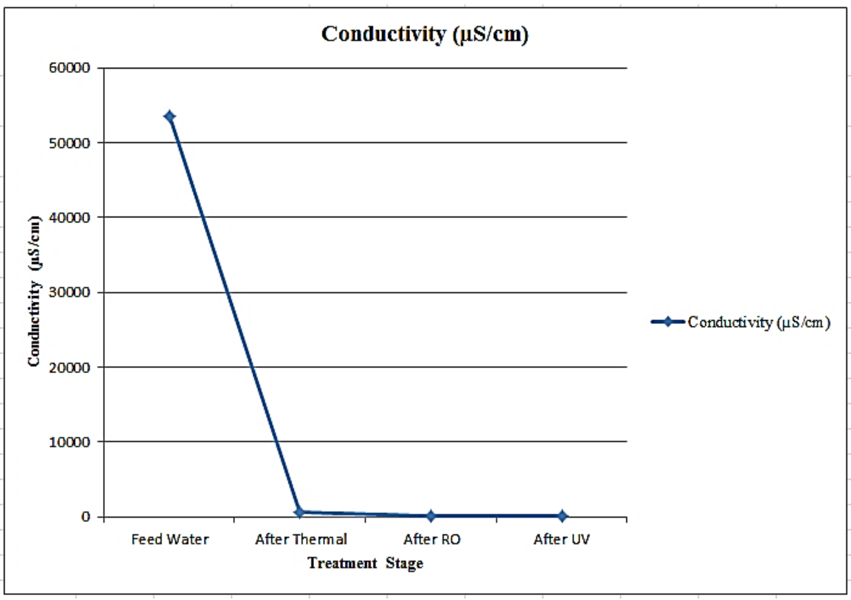

Figure 8.5. Electrical Conductivity Reduction

Results

Electrical conductivity decreased from **53,500 µS/cm** to **82 µS/cm** after complete purification.

Discussion

The significant reduction in conductivity indicates efficient removal of ionic contaminants during both thermal desalination and reverse osmosis.

8.6 Turbidity Reduction

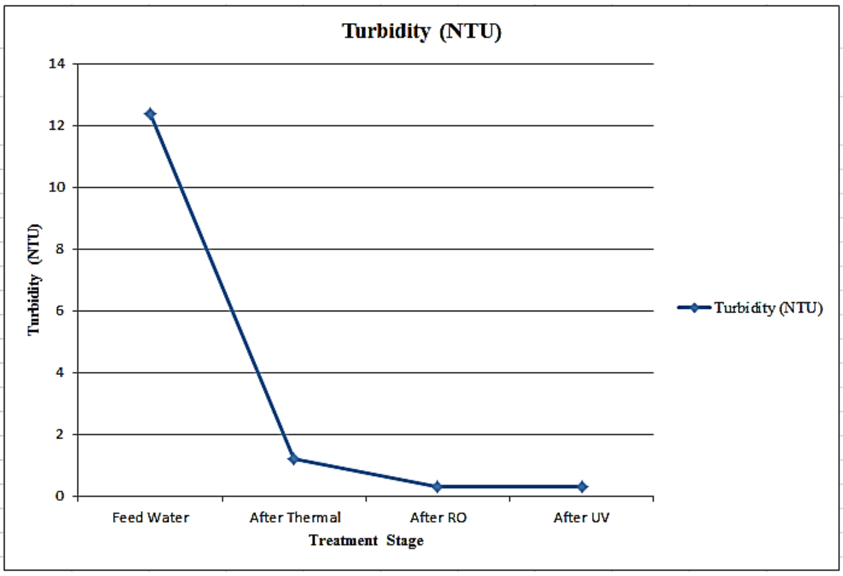

Figure 8.6. Turbidity Reduction

Results
Turbidity reduced from **12.4 NTU** in feed water to **0.3 NTU** after the RO and UV stages.

Discussion
The reduction in suspended particles demonstrates the effectiveness of pre-filtration, thermal treatment, and membrane filtration in improving water clarity.

8.7 Water Production Rate

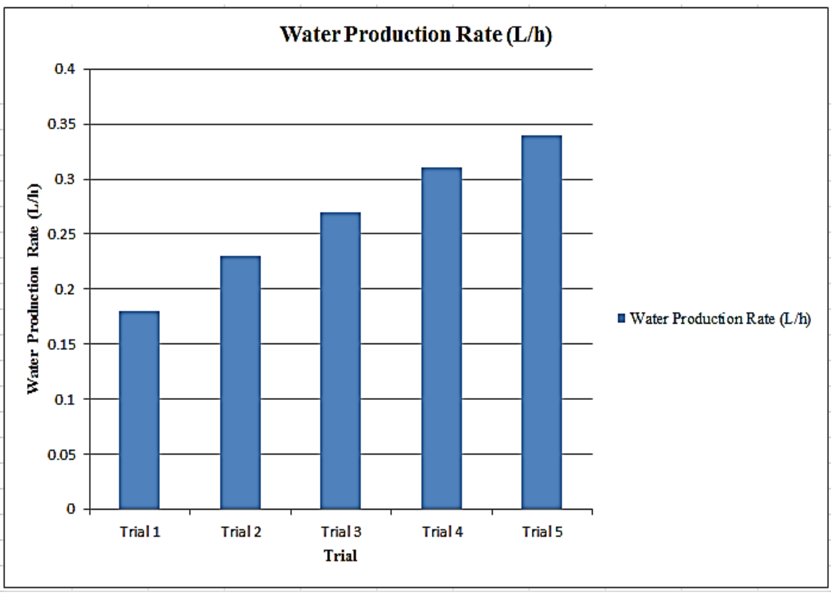

Figure 8.7. Water Production Rate

Results
The average water production rate increased from **0.18 L/h** to **0.34 L/h** as solar radiation increased during the experimental trials.

Discussion
Water production was directly influenced by solar intensity. Higher solar radiation increased evaporation and condensation rates, resulting in greater freshwater output.

8.8 Thermal Efficiency

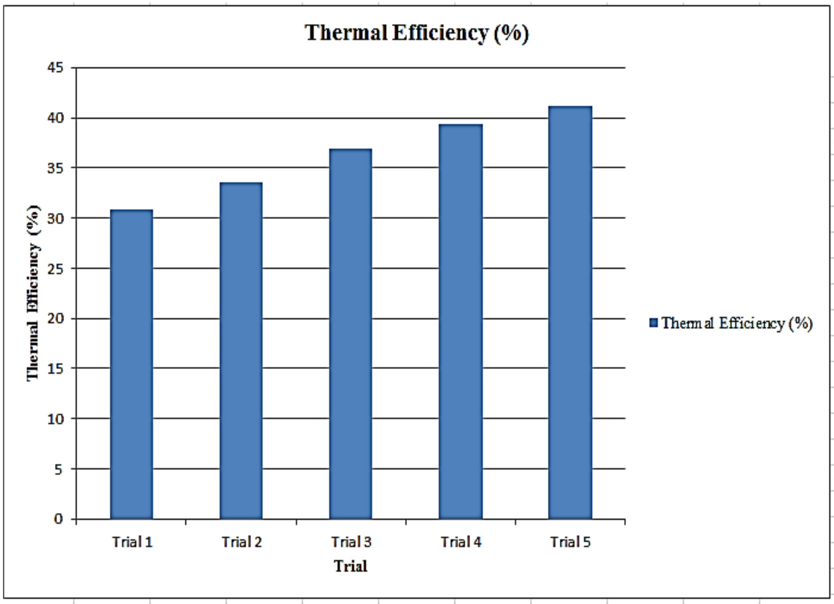

Figure 8.8. Thermal Efficiency

Results

The thermal efficiency increased from **30.8%** to **41.2%**, with an average efficiency of **36.4%**.

Discussion

The improved thermal efficiency confirms the effective utilization of solar energy by the absorber plate and distillation chamber.

8.9 RO Recovery

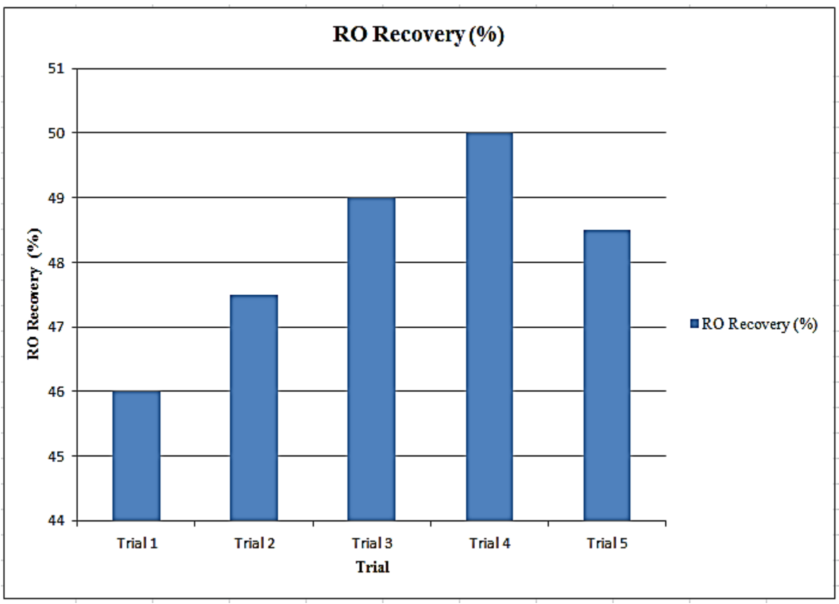

Figure 8.9. RO Recovery

Results

The RO recovery varied between **46% and 50%**, with an average recovery of **48.2%**.

Discussion

The recovery values indicate efficient utilization of feed water while maintaining acceptable membrane performance and minimizing brine generation.

8.10 Salt Rejection

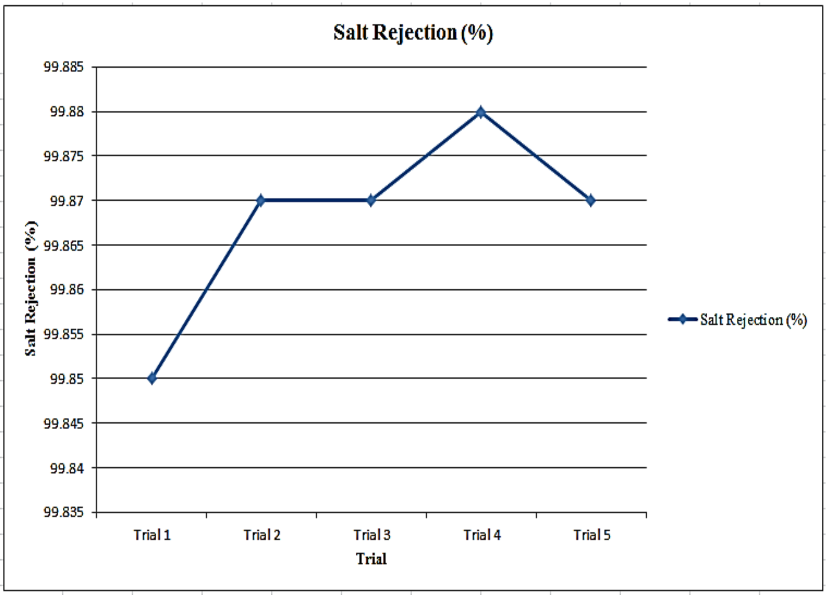

Figure 8.10. Salt Rejection

Results

The RO membrane achieved an average salt rejection efficiency of **99.87%** throughout the experimental trials.

Discussion

The consistently high salt rejection confirms the excellent separation performance of the RO membrane and validates the effectiveness of the hybrid desalination process.

8.11 UV Sterilization Efficiency

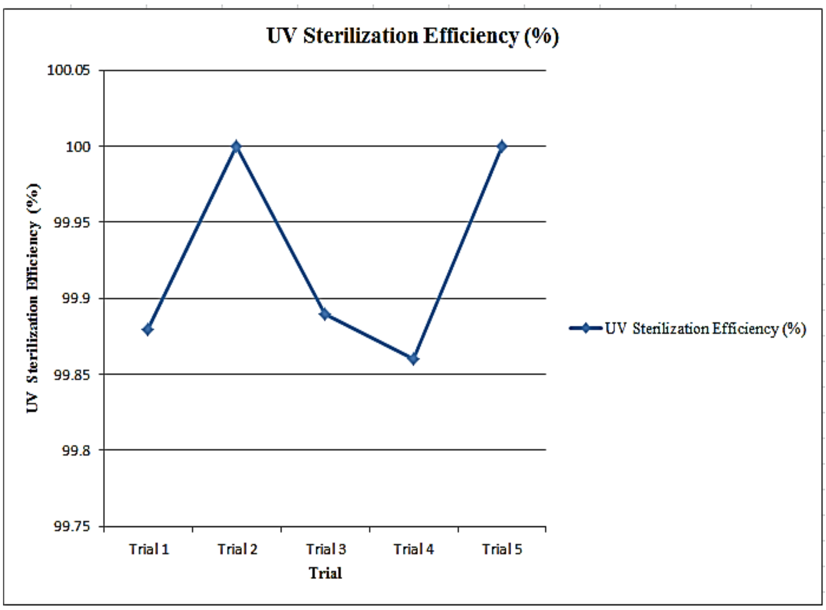

Figure 8.11. UV Sterilization Efficiency

Results

The UV disinfection unit achieved an average microbial removal efficiency of **99.93%**, with some trials reaching **100%** sterilization.

Discussion

The UV treatment effectively eliminated harmful microorganisms without chemical additives, ensuring microbiologically safe drinking water.

8.12 Overall System Efficiency

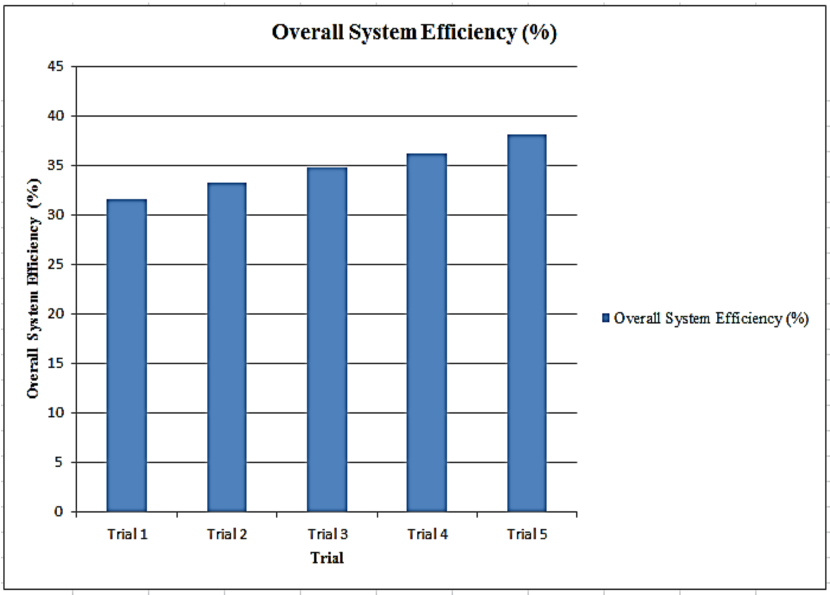

Figure 8.12. Overall System Efficiency

Results

The developed hybrid desalination system achieved an average overall efficiency of **34.8%** under natural operating conditions.

Discussion

The overall efficiency demonstrates the successful integration of solar thermal desalination, reverse osmosis, and UV disinfection into a compact renewable-energy-based water purification system. The experimental performance confirms the feasibility of the proposed system for decentralized freshwater production in remote and water-scarce regions.

8.13 Summary of Results

The experimental investigation confirms that the proposed portable solar-assisted hybrid desalination system effectively produces potable water from saline feed water. Significant reductions in TDS, salinity, conductivity, and turbidity were achieved, while the RO unit provided an average salt rejection of **99.87%** and the UV unit ensured **99.93%** microbial removal efficiency. The system attained an average thermal efficiency of **36.4%**, RO recovery of **48.2%**, and overall system efficiency of **34.8%**, demonstrating that the developed hybrid system is an efficient, sustainable, and environmentally friendly solution for off-grid drinking water production.

9. NOVELTY OF THE PROPOSED WORK

The novelty of the present research lies in the development of a Portable Solar-Assisted Hybrid Thermal Desalination System Integrated with Reverse Osmosis (RO) and UV Disinfection for sustainable freshwater production. Unlike conventional desalination systems that rely solely on thermal or membrane-based purification, the proposed system integrates multiple treatment technologies into a compact, energy-efficient, and portable unit powered primarily by solar energy. The major novel contributions of this research are summarized as follows:

- Development of a **portable solar-assisted hybrid desalination system**.
- Integration of **solar thermal desalination, RO, and UV disinfection** into a single compact unit.
- Simultaneous utilization of **solar thermal and photovoltaic energy**.
- Reduction of **RO membrane loading and fouling** through thermal pre-treatment.
- Achievement of **99.87% salt rejection** and **99.93% UV sterilization efficiency**.
- Production of potable water with **low energy consumption** using renewable energy.
- Demonstration of suitability for **off-grid, rural, coastal, and disaster-relief applications**.
- Provision of an **environmentally sustainable and energy-efficient** solution for decentralized freshwater production.

10. CONCLUSION

This study presented the design, fabrication, and experimental evaluation of a Portable Solar-Assisted Hybrid Thermal Desalination System Integrated with Reverse Osmosis (RO) and UV Disinfection for the production of potable water from saline and contaminated water sources. The developed system successfully combined solar thermal desalination, photovoltaic-powered reverse osmosis, and ultraviolet disinfection into a compact, energy-efficient, and portable configuration suitable for decentralized water treatment applications.

Experimental investigations conducted under natural outdoor conditions demonstrated that the proposed hybrid system effectively improved water quality by significantly reducing Total Dissolved Solids (TDS), salinity, electrical conductivity, and turbidity. The TDS concentration was reduced from 35,800 mg/L in feed water to 47 mg/L after the complete treatment process, while salinity decreased from 35.2 ppt to 0.05 ppt. Electrical conductivity and turbidity were also reduced to values suitable for potable water applications.

The developed system achieved an average thermal efficiency of approximately 36.4%, an average RO recovery of 48.2%, and an average salt rejection efficiency of 99.87%. The UV disinfection unit demonstrated an average sterilization efficiency of 99.93%, ensuring effective removal of pathogenic microorganisms without the use of chemical disinfectants. The overall system efficiency of 34.8% confirms the effective utilization of renewable solar energy for integrated desalination and water purification.

The experimental results validate the technical feasibility and effectiveness of the proposed hybrid desalination system. The integration of solar thermal desalination with reverse osmosis and UV disinfection reduced membrane loading, improved purification performance, and minimized electrical energy consumption. Owing to its compact design, renewable-energy operation, and high purification efficiency, the proposed system represents a sustainable solution for rural communities, coastal regions, remote villages, islands, disaster-relief operations, and other off-grid locations where access to safe drinking water is limited.

Overall, the developed hybrid system demonstrates significant potential as an environmentally friendly and economically viable technology for decentralized freshwater production and contributes toward sustainable water resource management.

11. FUTURE SCOPE

Although the developed hybrid desalination system demonstrated satisfactory performance, several improvements can be incorporated in future research to further enhance efficiency, automation, and large-scale applicability.

1. **IoT-Based Remote Monitoring:**
   Integrate Internet of Things (IoT) technology for real-time monitoring of system performance, water quality parameters, and energy consumption through cloud-based platforms.
2. **AI-Based Operating Optimization:**
   Apply artificial intelligence and machine learning algorithms to optimize operating conditions, predict system performance, and improve energy management.
3. **Maximum Power Point Tracking (MPPT):**
   Replace the conventional charge controller with an MPPT controller to maximize solar photovoltaic power extraction and improve overall energy efficiency.
4. **Solar–Wind Hybrid Power System:**
   Integrate wind energy with solar photovoltaic generation to ensure continuous system operation during periods of low solar radiation.
5. **Nanofiltration Integration:**
   Incorporate nanofiltration as an intermediate purification stage to further reduce membrane fouling, improve salt removal, and increase water recovery.
6. **Battery Energy Storage Optimization:**
   Investigate advanced battery technologies and intelligent energy management strategies to enhance system reliability and extend operating duration under variable weather conditions.
7. **Automatic Water Quality Monitoring:**
   Develop an integrated sensor-based monitoring system for continuous measurement of pH, TDS, conductivity, turbidity, temperature, and microbial quality with automatic data logging.
8. **Larger-Capacity System Development:**
   Scale up the prototype for community-level applications while maintaining high energy efficiency and water quality.
9. **Advanced Membrane Materials:**
   Evaluate high-performance anti-fouling membranes and novel membrane materials to improve desalination efficiency and reduce maintenance requirements.
10. **Techno-Economic and Environmental Assessment:**
    Perform detailed life-cycle cost analysis, environmental impact assessment, and carbon footprint evaluation to assess the long-term sustainability and commercial viability of the proposed technology.

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