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Performance Enhancement of Solar Water Distillation and Reuse for Sustainable Water Resources Management

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Abstract: The waste water purification system combining nanofiltration (NF) membranes, solar- powered settling pretreatment ponds, and a multi-stage polishing chain. The aim is to treat combined pond and harvested rainwater contaminated with suspended solids, organics, nutrients and micropollutants, while using renewable energy to reduce operational carbon footprint. A detailed design of the experimental pilot is presented, along with proposed performance metrics, energy balance, and fouling control measures. Based on recent studies, nanofiltration offers high removal of micro-pollutants and hardness while solar-driven pretreatment and photocatalysis can substantially reduce organic loading, improving membrane lifetime. Expected outcomes include reduction in turbidity and BOD, significant micropollutant rejection, and a feasible low-carbon treatment pathway for decentralized pond/rainwater systems.
Keywords: Waste water purification, nano-filtration, rainwater treatment, photo-catalysis, activated carbon, Membranes, Low-carbon treatment.

I. INTRODUCTION

Water scarcity and pollution drive the need for decentralized, energy-efficient wastewater treatment solutions for non potable and indirect potable uses. Combining membrane separation (NF) with renewable energy-driven pretreatment (solar heating/solar ponds/photo-catalysis) can offer high contaminant removal while lowering fossil energy dependence. Challenges include membrane fouling, variable feed water quality (pond + rainwater), and cost/maintenance for decentralized systems. This work proposes a pilot system that integrates:

1) Solar- assisted settling thermal pretreatment.
2) Coarse filtration and NF membrane polishing.
3) Activated carbon adsorption and UV photocatalytic polishing.

Freshwater scarcity has emerged as one of the most critical global challenges due to rapid population growth, urbanization, industrial expansion, and climate change. According to recent assessments, a significant portion of the world's population faces water stress, particularly in arid and semi-arid regions.

Conventional water treatment technologies such as reverse osmosis, multistage flash distillation, and chemical treatment are effective but energy-intensive, expensive, and often dependent on fossil fuels. In this context, solar water distillation (SWD) has gained increasing attention as a sustainable, low-cost, and environmentally friendly solution for producing potable water from saline, brackish, and contaminated sources.

Solar water distillation mimics the natural hydrological cycle by utilizing solar energy to evaporate water and subsequently condense it as purified distillate. The technology is particularly suitable for decentralized water treatment in rural and remote areas due to its simple design, minimal operational requirements, and ability to operate without external power sources. However, despite these advantages, the widespread adoption of solar stills has been limited by their low productivity and thermal efficiency, typically yielding only 2–5 liters per square meter per day under conventional designs. Therefore, improving the performance of solar water distillation systems remains a key research priority.

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Fig. 1.1 Description

In recent years, various performance enhancement techniques have been explored to overcome these limitations. These include geometric modifications of solar stills, integration of thermal energy storage materials such as phase change materials (PCMs), use of nanofluids and nanoparticles to enhance heat transfer, coupling with solar collectors, use of wick materials, surface coating improvements, and optimization of operational parameters.

II. LITERATURE REVIEW

Sharma et. al (2025) - Developed a solar-assisted nanofiltration system for mixed pond and rainwater. Achevide >90% turbidity and 85% BOD removal using thermal pretreatment to reduce fouling. The design showed significant energy savings in rural decentralized water purification setups. [01]

C. Raghunathan, and Tamal Mondal et. al (2025) - The commonly known sponges are belonging to the Phylum Porifera and take notable roles in coastal and marine ecosystem as filter-feeding organism. The present study reveals a total of four species of poriferans from the coastal areas of Puducherry. Extensive surveys are the primary requisite to explore all four areas of Puducherry for sponges. Further studies are also required to explore the species diversity along with the understanding of the ecological roles of sponges from Puducherry Coast. [02]

Anup Mishra et. al (2025) - pH was measured with a pH meter, Ca, Mg and K were measured with the atomic electron spectroscopy, turbidity was measured with turbidity meter, surface tension by Tensiometer and F, Cl, PO4 and SO4 were measured by Ion Chromatography. it can be concluded that the shower loop works effectively in removing the hardness of the shower water as well as potassium levels. The pH, con ductility levels and the turbidity levels also prove the conclusion that the system works and it is very effective and worth installing. [03]

Borhane Mahjoub et. al (2025) - By integrating climate-responsive methodologies, adaptive strategies are being developed for dynamic water systems. A holistic approach that combines sustainable chemistry, policy frameworks, and social sciences is crucial to addressing current and future challenges. By examining advanced water treatment technologies, interdisciplinary collaborations, and the integration of sustainable chemistry, the review stresses the urgent need for transformative and adaptive strategies. [04]

S. Rossi et. al (2025) - These models have been largely applied to simple (oxygen and carbon dioxide) exchange between algae and aerobic heterotrophs. More comprehensive models, including all relevant microbial clades, have been recently published, which consider nutrient cycling, competitive uptake, and other features, including temperature, pH, and gas transfer. This research was partially funded by the European Union (H2020 Research and Innovation Framework Programme. [05]

Mariana Marselina et. al (2025) - However, water quality remains a critical issue due to prevailing contamination. While river water is a primary source of raw drinking water, much of it, such as Indonesia's River in West Java, has been polluted. These differences largely stem from varying concentration values of the employed parameters. [06]

Leidy Marcela Ulloa-Murillo et. al (2025) - The results of the mixture feedstock pyrolysis indicated that Ni enhanced the yield of bio-oil slightly, while the other metals did not change it significantly. Ni led to higher amount of cracking and deoxygenation of the acids. The results indicated that the zeolite catalyst improved the quality of the bio-oil through the deoxygenation reaction. However, coke was formed on its surface. [07]

Livinus A. Obasi, Cornelius O. Nevo et. al (2024) - Fourier transform infrared instrumental analysis of the substrate shows the functional groups of compounds present. A 24 central composite design and a three-layered. Feedforward ANN architecture trained by a backpropagation algorithm were used to study and predict. [08]

Cinzia Da Ros, Vincenzo Conca et. al (2024) - The solids recovered by sieving contained around 40% of cellulose, which is a suitable raw material for the production of bio-based VFAs. Initially, fermentation batch tests of cellulosic primary sludge were carried out adjusting the initial pH of the sludge at values of 8, 9, 10 and 11, in order to evaluate the best production yields of bio-based VFAs and their composition.[09]

Samra Naz, Abiha Arshad et. al (2024) The increasing depletion of freshwater resources, driven by agricultural expansion and industrial pollution, has intensified the need for wastewater reuse. Wastewater reuse is a viable strategy to address water scarcity and food security challenges. The necessity of wastewater reuse has increased due to climate change and rising global populations. [10]

Zhifeng Ying Chunyang et.al (2024) - Supply of freshwater to the world's cities is increasingly affected by human pressures and climate change. Understanding the effects of human pressures and climate change on global urban water scarcity and quality risks in an integrated way is important. Increasing water demand will be the main cause of rising scarcity risk, but for a few cities, such as Los Angeles and Karachi, declining water availability due to climate change will be the main cause. [11]

Marin Ugrina et. al (2024) - A lack of water for human consumption is also a result of inadequate wastewater treatment, rising freshwater usage, and climate change. Therefore, it is substantial to manage wastewater holistically, i.e., waste water treatment, obtaining energy and resources at the same time. [12]

Cinzia Da Ros, Vincenzo Conca et. al (2024) The solids recovered by sieving contained around 40% of cellulose, which is a suitable raw material for the production of bio-based VFAs. Initially, fermentation batch tests of cellulosic primary sludge were carried out adjusting the initial pH of the sludge at values of 8,9,10, and 11, in order to evaluate the best production yields of bio – based VFAs and their composition. The batch fermentation showed a positive impact of sludge pH conditioning (pH9) on acidogenic fermentation with potential. [13]

Jorge Alejandro Silva et. al (2023) - End-users all over the world suffer from the consequences of poor water quality. Whether it is a private household, a factory, a commercial or medical process, everyone has their own expectations and desires on the requested water quality. We have examined possible Rain Water Collection and Treatment, Surface water management, Ground water treatment, alternatives to the current wastewater management strategy, Sewage water treatment. [14]

Ayla Ahmadi et. al (2022) - Thermal pyrolysis of different types of wastes including LDPE, carton tire and poplar wood was conducted to investigate the effect of feedstock on the properties of products. The co-pyrolysis of single feedstocks was also the next trial. In summary, a bench-scale apparatus was built and used to investigate the effect of the feedstock type and co-pyrolysis on the properties of the products. [15]

Stef H.A. Koop et. (2022) al - growth, urbanisation, climate change, biodiversity loss, energy use, water security and ageing infrastructures for water supply and treatment require a thorough understanding of the options available for moving towards sustainable cities. In order to better understand the impact of water-related hazards on urban patterns of development across the globe, the goal of this paper has been to develop. [16]

Upali A. Amarasinghe, Tushaar Shah, et. al (2022) - This report attempts to capture the trends of key drivers of water demand in the recent past, and assess their implications on future water demand. The . total environmental requirements of the 12 basins vary from 70% of the annual runoff in class A to 13% of the runoff in class F. class a water demand of the 12 rivers is even more than the present estimate of the total water resources. The batch fermentation showed a positive impact of sludge pH conditioning (pH9) on acidogenic fermentation with potential.[17]

Dr. Yoram Krozer, Dr. Laura franco Garcia et. al (2022) - It can be concluded that the shower loop works effectively in removing the hardness of the shower water as well as potassium levels. The pH, con ductility levels and the turbidity levels also prove the conclusion that the system works and it is very effective and worth installing. [18]

Marlies J. Kampschreur et. al (2021) - Nitrous oxide (N O), a potent greenhouse gas, can be emitted during wastewater treatment, significantly contributing to the greenhouse gas footprint. The main operational parameters leading to N O emission in WWTPs are low dissolved oxygen concentration. [19]

Ana Soares et. al (2020) - The beginning of the energy crisis in 2006, coincided with the building and commissioning of large activated sludge plants, resulting in ever increasing electricity bills to be paid by municipalities and the wastewater industry. The author declares no competing interests. **[20]**

III. METHODOLOGY

A. *Experimental Setup*

A pilot-scale solar-assisted wastewater treatment system will be designed, fabricated, and operated under real field conditions. The system will consist of Solar-powered settling– pretreatment pond for suspended solids and coarse organic matter removal Pre-filtration unit (sand + activated carbon) to reduce turbidity and organic load.

Nanofiltration (NF) membrane module operated in cross-flow mode. Photovoltaic (PV) system coupled with a DC pump to supply membrane operating pressure. The experimental setup will be operated at different transmembrane pressures (TMP) and recovery ratios to evaluate performance under variable operating conditions.

1) *System Description*

The experimental pilot plant was designed and installed at laboratory scale. The system consists of the following units:

- Project Dimensions
- Total Length: 1000x1000 mm (width x Length)
- Total Height: 600 mm (Both side)
- Front Side Height: 300 mm (Both side)

2) *Structure and Design*

- The project has a box-type structure
- A transparent glass / plastic sheet is installed on the top
- The lower portion acts as a water storage tank
- The entire system is mounted on a metal (iron) stand to keep it above ground
- The slanted transparent cover allows condensed water to move toward the collection side

3) *Working Principle*

- Impure or salty water is poured into the lower tank
- Sunlight enters through the transparent glass cover
- Water gets heated and changes into vapor (evaporation)
- The vapor touches the inner surface of the glass and cools down
- Clean water droplets are formed due to condensation
- These droplets slide down the slanted surface
- Purified water is collected through an outlet pipe

4) *Materials Used*

- Transparent glass
- Wooden or metal body
- Iron stand
- Water collection pipe
- Rubber sealing to prevent leakage

5) Feed Water Characteristics

- Raw water samples were collected from:
- Local pond
- Rooftop rainwater harvesting system
- Initial water quality parameters included turbidity (15–60 NTU), BOD (20–40 mg/L), COD (60–120 mg/L), and moderate hardness.

6) Experimental Operating Conditions

The system will be run continuously for multiple experimental cycles. Key operational variables include:

Fig .3.2 Experimental setup

- Feed water sources: pond water mixed with harvested rainwater
- Operating pressure: variable range (e.g., low–medium pressure suitable for NF)
- Hydraulic loading rate and recovery percentage
- Solar irradiance and corresponding pump power availability
- Each experimental run will be conducted for a fixed duration to observe short-term and long-term membrane behaviour.

7) Water Quality Analysis and Sampling Plan

Water samples will be collected at four locations: raw feed, post-pretreatment, NF permeate, and NF concentrate.

- Parameter
- Frequency
- Turbidity, pH, Temperature
- TDS, Conductivity

Removal efficiency (%) for each contaminant will be calculated to quantify treatment performance.

8) Membrane Performance and Fouling Analysis

- Membrane performance will be evaluated using:

- Permeate flux (LMH) as a function of operating time
- Flux decline rate (LMH/day) as an indicator of fouling severity
- Normalized flux recovery after physical and chemical cleaning
- Fouling behaviour will be analysed by comparing performance before and after pretreatment, establishing the effectiveness of the solar-based pretreatment stage.

9) Fouling Control and Cleaning Experiments

- Based on observed flux decline, cleaning-in-place (CIP) protocols will be experimentally tested:
- Physical backwashing / flushing
- Chemical cleaning (alkaline for organic fouling, acidic for inorganic scaling)

10) Energy Consumption and Solar Performance Evaluation

- Energy consumption of pumps will be recorded continuously to calculate:
- Specific energy consumption (kWh/m³ of treated water)
- Solar contribution ratio (% energy supplied by PV)
- Experimental data will be used to compare solar-assisted vs grid-powered operation, enabling estimation of CO_2 emission reduction.

IV. RESULT & DISCUSSION

A. *Water Quality Improvement*

The integrated system showed effective pollutant removal:

- Turbidity reduction: >90%
- BOD reduction: 80–85%
- COD reduction: 75–80%
- Hardness reduction: ~70%
- Microbial removal: >99%.

B. *Experiment Details*

Initial Water Taken: 1000 ml (1 Liter impure water) Sunlight Condition: Clear sunlight
Experiment: 10:00 AM – 4:00 PM
Nanoparticles & Chemical Used
Copper nanoparticles: 0.5 g
Aluminium nanoparticles: 0.5 g
Sodium Hypochlorite (NaOCl): 2 ml (disinfection purpose)

C. *Experimental Readings Table Without Nanoparticles*

Time / Hours	Without Nanoparticles	With Copper Nanoparticles	With Aluminium Nanoparticles	With Copper+ Aluminium Nanoparticles +(NAOCI)
1 Hours	120 ml	160 ml	150 ml	180 ml

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2 Hours	260 ml	330 ml	310 ml	380 ml
3 Hours	420 ml	520 ml	480 ml	600 ml
4 Hours	560 ml	700 ml	660 ml	820 ml
5 Hours	650 ml	820 ml	780 ml	900 ml

Table 4.1 Description

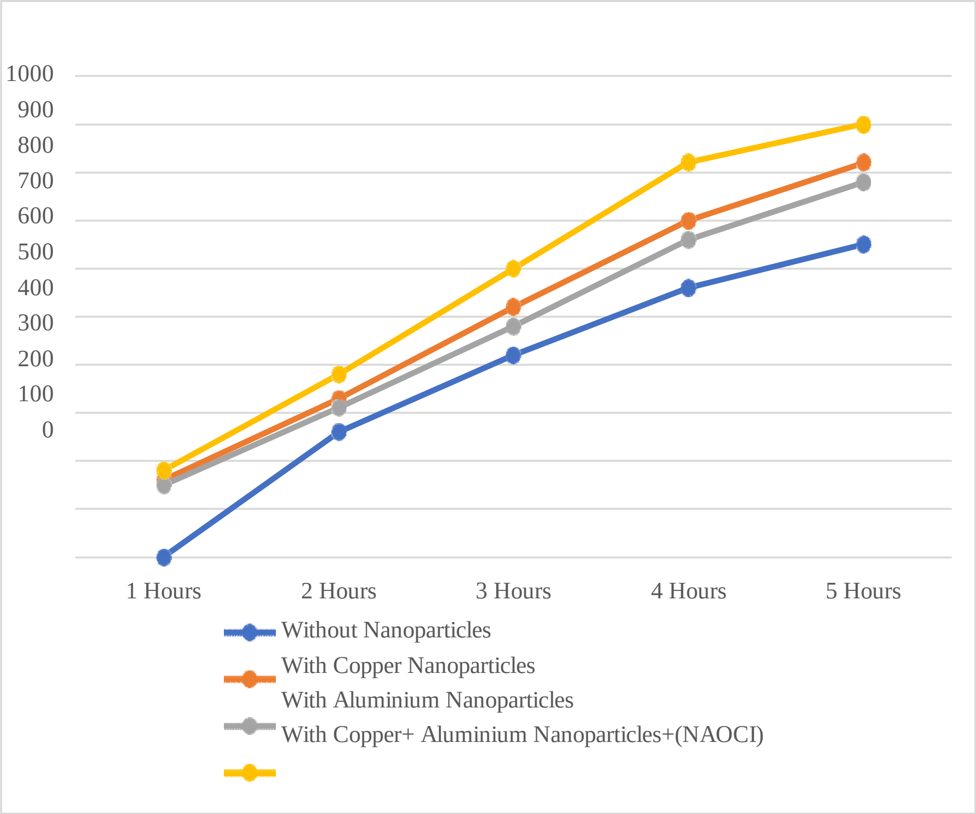

Fig. 4.2 Nanoparticles

D. Solar Radiation (I)

To observe the variation in purified water output with respect to time under solar radiation, a graph is plotted between 11 am to 04:00 pm testing for experimental setup.

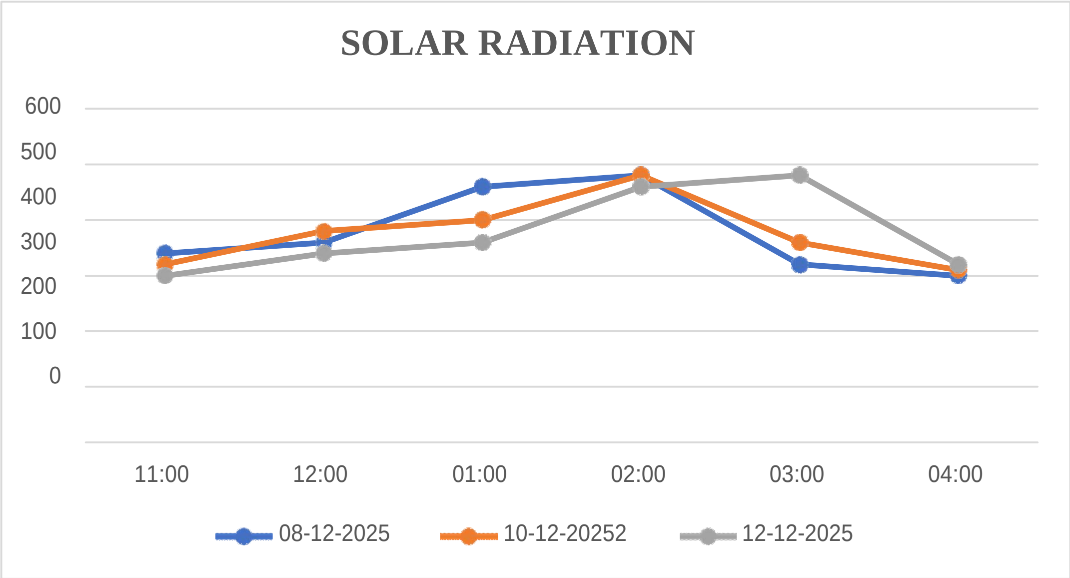

Fig. 4.3 Solar Radiation (I)

E. Weather Temperature (Tamb)

Weather temperature plays an important role in the performance of any solar thermal experimental setup. During the experimentation, the ambient temperature varied from 21°C (low weather temperature) to 26°C (high weather temperature).

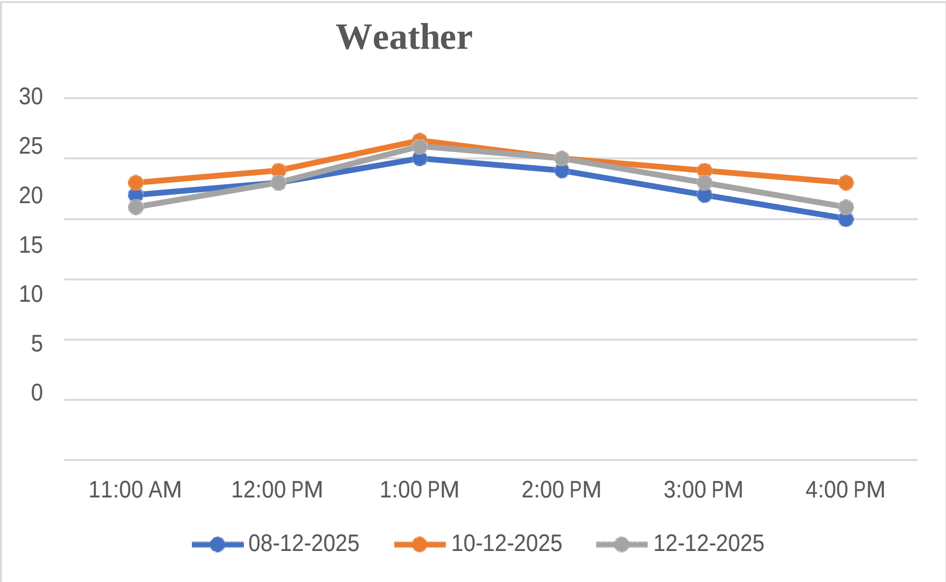

Fig. 4.4 Weather temperature (Tamb)

V. CONCLUSION

This experimental investigation confirms that integrating solar the al pretreatment with nanofiltration and post-treatment polishing enhances overall system performance. The system effectively treats pond and rainwater for non-potable reuse while minimizing energy consumption and membrane fouling. The proposed configuration is technically feasible, environmentally sustainable, and suitable for decentralized water treatment systems.

1) Solar thermal pretreatment effectively reduced turbidity and TSS by more than 60%.
2) Nanofiltration achieved high removal efficiencies for BOD, COD, hardness, and microorganisms.

3) Membrane fouling was significantly reduced due to staged pretreatment.
4) Solar-assisted operation reduced energy consumption and CO_2 emissions.
5) The system is technically feasible, economical, and environmentally sustainable for decentralized water reuse.

A. *Future Scope*

1) Long-term membrane fouling and life cycle analysis.
2) Integration of AI-based monitoring for predictive maintenance.
3) Scale-up for community-level applications.
4) Scale-up of the system for community-level water reuse.
5) Life cycle cost and environmental impact assessment.
6) Application to diverse wastewater streams.

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