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SOLAR STILL ADVANCEMENTS PCM AND NPCM APPLICATIONS FOR EFFICIENT TREATMENT OF WATER: AN EXPERIMENTAL APPROACH

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Abstract
The experiment compared three solar still designs that were employed: simple solar still (SS), solar still with phase change material (PCM), and solar still with phase change material and nanoparticles (NPCM), using water from different sources in Shahdol, Madhya Pradesh, India. Samples W1, W2, W3, and W4 were tested for parameters like TDS, turbidity, pH, and total hardness. Water from all three systems met BIS-10500 chemical standards. Sample W2, with the least contamination, showed the highest SS productivity at 1997 ml/m2/day. High pollutant contamination hindered the evaporation process, reducing vapor pressure and solar radiation transmissibility. PCM yielded 3220 ml/m2/day, while NPCM reached 4305 ml/m2/day. The NPCM system consistently outperformed, producing 3250 ml/m2 for W1, 3510 ml/m2 for W3, and 2860 ml/m2 for W4. The study highlights NPCM's superiority in water production over other solar stills, emphasizing its potential for efficient fresh water generation.
Keywords: Solar still, PCM, NPCM, TDS, Vapor pressure, BIS-10500

1. Introduction

Worldwide, there are number of rural areas with inadequate sanitary infrastructure, which results in poor wastewater treatment techniques that worsen contamination in the environment. The unavoidable accumulation of clean wastewater in these localities is a primary cause of water contamination, which in turn leads to the dissemination of illnesses in remote areas [1]. There exists a strong correlation between lifestyle modifications, economic growth, and the increasing energy demand in developing nations such as India [2].Our growing need for energy has made us consider the impending exhaustion of natural resources. Developing countries like China and India have faced environmental problems in recent decades as a result of over-exploitation of their resources [3, 4]. Mining is a site-specific industry that is engaged in when significant mineral deposits are made [5]. There are four varieties: placer, open surface (pit), subterranean, and in-situ. Minerals are extracted from below the surface and processed in underground mining [6]. Energy-intensive wastewater treatment is required, especially in municipal or industrial waste water treatment plant. The energy spent per kilogram of bio chemical oxygen demand (BOD) removed (kWh kg -1) and the energy used per million gallons of treated wastewater (kWhMG-1) is important metrics for evaluating energy consumption in this context. However, the average energy use per million gallons of treated wastewater is roughly 1084.23 kWh MG-1, the average energy consumption for various secondary treatment procedures is approximately 0.57kWh kg-1 [7]. The future of India is greatly bolstered by solar energy due to its favorable positioning and synergistic compatibility with other renewable resources. Water purification treatment has been accomplished by the utilization of many methods, such as membrane distillation, charcoal filtration, electrodialysis, thermal vapor compression, reverse osmosis, andactive UV radiation. These approaches are generally characterized by higher costs and greaterenergy consumption. However, as technology advances and their acceptance increase, they may become more cost-effective and suitable overtime [8].As a result, numerous scientists investigated the theoretical and experimental capabilities of solar stills in the context of water purification. Due to their cost-effectiveness and water purification capabilities, solar stills have gained popularity [9-11]. Solar stills show promise as non-conventional waste water treatment solutions considering the increased attention being paid to waste water treatment and the increasing use of renewable energy sources in many different areas of the economy [12]. The solar technology continues to be the most basic, which makes it the best option for use in distant and rural locations. A solar still, sometimes known as a "green energy process," uses the sun's plentiful natural energy to purify contaminated water and produce drinkable water. For the purifying process, this approach uses solar energy rather than more traditional sources like fossil fuels, oil, or gas [13, 14]. Their findings indicated that the primary limitation of the solar system was its reduced efficiency in terms of output [15]. Researchers from various parts of the globe have undertaken numerous investigations aimed at enhancing the productivity of solar stills. Most of these studies have found that elements like the surface area for heat absorption, the angle of tilt, heat transfer mechanisms, water depth, evaporation surface, heat dissipation (especially through side and bottom walls), and the temperature of the glass cover significantly affect the efficiency of solar stills [16-18]. The fundamental variant of solar distillers is the single-slope distillation unit, which lacks an energy storage mechanism. Among more sophisticated solar distillation units, these basic units exhibit the lowest productivity. In traditional solar still setups, incorporating diverse energy storage materials and modifying operational modes has the potential to amplify the output of distilled water. Solar distillation units can be divided into two main categories: passive and active solar stills. These two types possess advantages and disadvantages stemming from their distinct operational modes and associated costs [19-21].Inactive solar stills, water evaporation occurs at an accelerated pace due to the introduction of supplementary heat energy from an external source. This additional heat can originate from various sources, such as concentrator or collector panels, as well as residual heat from chemical or industrial facilities. On the other hand, passive solar distillation units operate on the principle of natural convection, resulting in comparatively lower productivity when compared to active solar stills. However, they offer the advantage of being cost-effective and user friendly [22-24].Enhancing the daily efficiency of passive solar distillation units has the potential for significant improvement through the incorporation of PCM. This material can store energy and subsequently release it as heat during the evening hours, utilizing the energy accumulated as latent heat, sensible heat, or even a combination of both, throughout the sunny periods [25-27].The solar irradiation in a solar desalination system is minimally influenced (neither scattered nor absorbed significantly) by tap water. However, the actual waste water compositions contain highly concentrated ions, which can substantially impact the transmission of solar irradiation to the basin during evaporation. The passage of incident radiation through contaminated water results in a decrease in transmittance. Consequently, the presence of highly concentrate Pollutants in the water can lead to a significant reduction in solar energy [28]. The presence of a high concentration of pollutants in water, which lowers vapor pressure, contributes to a comparatively slower rate of evaporation [29].

The focus of this investigation is the viability of employing solar stills for water treatment. A single-slope solar still has been fabricated, and four types of water samples were collected from different sources situated in Shahdol, Madhya Pradesh, for this study. After the collection of samples, they were subjected to analysis in a solar still. The results revealed significant improvements in the water's TDS, TSS, turbidity, and pH values, rendering it suitable for use. Solar stills prove to be a viable option for treating contaminated water, offering economic benefits. Three different designs of solar still SS, PCM, and NPCM were employed, among which the NPCM system demonstrated the highest productivity, making it a superior choice for ensuring clean water supply. Additionally, it has been observed in this experiment to explore the lower evaporation rate of highly contaminated water. This phenomenon is attributed to the reduced vapor pressure and decreasing transmissibility of solar radiation in contaminated water. However, such research findings have not been identified in the existing literature.

The requirement for treatment of waste water

Water treatment is essential to safe guarding the environment and human health by removing pollutants and contaminants. Effective waste water treatment helps prevent the spread of water borne diseases and protects ecosystems from the harmful impacts of untreated sewage and industrial effluents. An earlier investigation revealed that even at a low concentration of 0.005mg/L, exposure to lead in drinking water resulted in kidney damage and a decrease in red blood cells count [30-32]. The study conducted by Fang et al. [33] found a correlation between long-term consumption of copper (Cu) and zinc (Zn) ions in drinking water and the increased risk of hypertension and heart disease in individuals. Moreover, the long-lasting existence of industrial dyes in the environment presents a substantial peril to both ecosystems and human well-being, considering the prolonged periods of time that pollutant in dye waste waters can persist, which range from 2 to 13 years. The rapid depletion of groundwater levels is a major factor in the occurrence of acute water scarcity in around 40 nations globally, as highlighted by Jasechko and Perrone [34]. Based on their research, out of the approximately 39million wells worldwide, only 5-20% indicated a decline in water levels of only 5 meters near the water table. In addition, information obtained from the Gravity Recovery and Climate Experiments (GRACE) carried out by the National Aeronautics and Space Administration (NASA) reveals substantial drops in ground water levels over an area exceeding150,000 square km globally. The in adequate consumption of calcium from drinking water has been associated with the development of osteoporosis (reduced bone density), kidney stones, colon cancer, hypertension, and obesity. Inadequate consumption of magnesium from drinking water can result in endothelial dysfunction, vascular actions, and a reduction in insulin sensitivity in the human body, as stated by the World Health Organization in 2009 [35].

Materials and Method

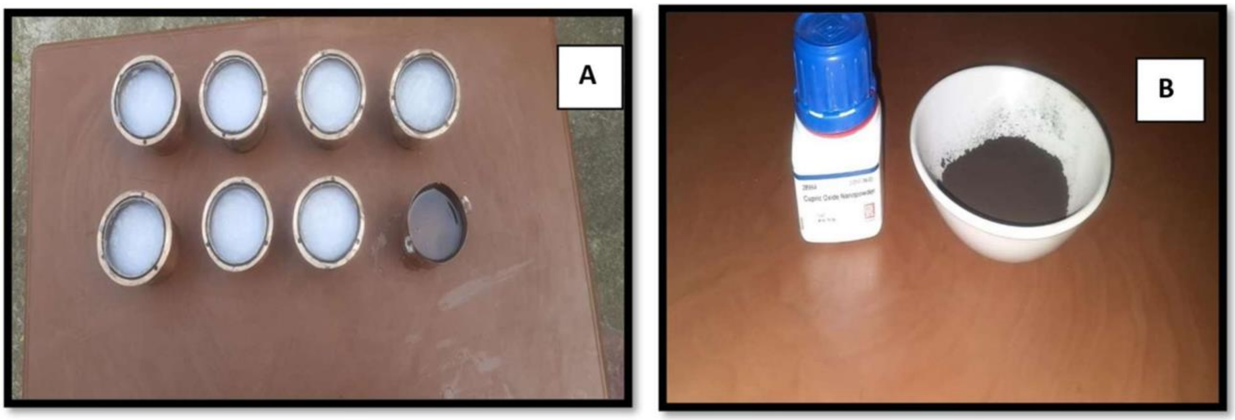
Geographical and metrological locations

The single slope solar stills have been investigated the government polytechnic college ground Shahdol, Madhya Pradesh with latitude and longitude angle of coordinates (23.3002o, 81.3569o)in the month of May.Figure1 shows the site location of experiment the average solar radiation of month of May is 590 W/m2 and wind speed 1 m/s. The location, Shahdol is an area located in the Southeastern Coalfields Limited (SECL) zone, known for its extensive coal deposits beneath the ground. The region faces significant challenges in terms of water pollution, with the surrounding areas heavily impacted by coalmining activities.

Figure 1 Location of experiment in the map

Materials and sample collection

Figures 2 (A, B) shows the copper cylinders containing PCM and NPCM. Because of its exceptional durability, non-toxic and non-corrosive qualities, and great heat conductivity, copper was selected as the building material for the cylinders. The instrument used was a Hot Disk TPS 500 Thermal Conductivity Analyzer, which has 99% accuracy rate and a measuring range of 0.022 to 100 W/m-k. Each of the eight copper cylinders held 1.7 kg of PCM or PCM with nanoparticles (containing 1 wt. % of PCM). Using a magnetic stirrer on a heated plate, the phase transition material and nanoparticles were combined.



Figures 2 A and B shows the copper cylinders containing PCM and NPCM

The thermo physical characteristics of PCM and NPCM are shown in Table 1. The testing was conducted at the Caustic Soda Unit of the Orient Paper Mills Industry in Amlai, District Anuppur Madhya Pradesh. A study was carried out to ascertain the thermal conductivity of NPCM.

Table1. Thermo physical properties of PCM and NPCM [27]

Properties	PCM	NPCM
Thermal conductivity,(w/m-K)	0.18	0.394
Density in solid, (kg/m^3)	849.9	880
Specific heatcapacity,(kj/kg ^{0}C)	2.96	2.88
Melting temperature (^{0}C)	36-60	36-60

Figures 3 shows the samples of water collected for experiment from different sources were collected from Dhanpuri coal mines, tap water, Murna River water, and Surfa dam water situated in the Shahdol, Sohagpur area, and their testing was conducted before and after the experiment. Table 2 displays the sample collection ID indicated by the names W1, W2, W3, and W4. A comparison of their chemical properties is presented in Table 3. It shows the value of different chemical parameters of water samples collected from different sources. Presently, all coal mines operate under the zero-pollution concept and recycle for different applications. The water sample was collected from Dhanpuri underground mines, tap water, Murna River water, and Surfa dam water for analysis. The teasing of water is done in the chemical laboratory of casting soda unit of orient paper mill. The tested parameters are the physico-chemical characteristics of water, which encompass pH, turbidity, total dissolved solids (TDS), total alkalinity, and total hardness [36-38]. The sample was analyzed using established procedures in compliance with the Bureau of Indian Standards (BIS, 1991) and the American Public Health Association (APHA, 2017) [39,40].

Figures 3 shows the samples of water collected for experiment from different sources

Table2 Water sample were collected from different locations

Site	Source	Sample ID
Dhanpuri underground mine	Coalmine water	W1
Dhanpuri supply water	Tap water	W2
Murna river water	Murna river	W3
Surfa dam water (industrial waste	Surfa dam	W4

Table 3 Value of different chemical parameters for the source of water samples [BIS1991,APHA-2017]

Chemical parameters	W1	W2	W3	W4	BIS-10500 desirable limit
pH	8.1	7.5	7.9	8.58	6.9-8.5
Turbidity NTU	15.9	0.7	12.7	4.5	1
TDS mg/L	970	550	725	3312	500
Total hardness mg/L	190	95	170	80	200
Total Alkalinity mg/L	250	120	190	584	200

Experimental setup

Figures 4 A and B shows a photographic view of a solar still that depicts the experimental set up of a passive solar still with a single slope (dimensions: 75 cm x 75 cm x 15 cm). Constructed from 1mm thick stainless steel, the solar still features a transparent glass cover inclined at 23° with a thickness of 4 mm. The basin is coated in black to absorb solar radiation, while the glass cover permits the passage of solar radiation while blocking infrared radiation, functioning as a condenser for the saturated vapor within. The angle between the inclined glass cover and the water basin, in particular, has a significant impact on the solar still's radiation shape factor. Interestingly, despite changes in the glass cover inclination, the distillation output remains largely consistent. Additionally, to improve thermal conductivity, eight copper cylinders filled with phase-change material or nanoparticles have been incorporated into the solar still. Each copper cylinder, with a diameter and height of 7 cm, was sealed with rubber rings to ensure the integrity of the phase change material or nanoparticles within the desired temperature range. In this study, four experiments were conducted to assess the daily productivity of water with different samples: a simple solar still (SS), a solar still with phase change material (PCM-based), and a solar still with nanoparticles (NPCM). The experiment was conducted in Shahdol, Madhya Pradesh, in May. It began at 8:00a.m. And ended at 8:00p.m.The weather stayed clear during the observation period. However, up until the point at which distillation and heat transmission ended, measurements of all temperatures and solar radiation intensity were made hourly. Temperature readings were taken inside the solar still at several points using P-T100 thermocouples. Table 4 displays the experimental variables utilized in the experiment, while Table 5 displays all of the calibrated equipments used in the experiment.

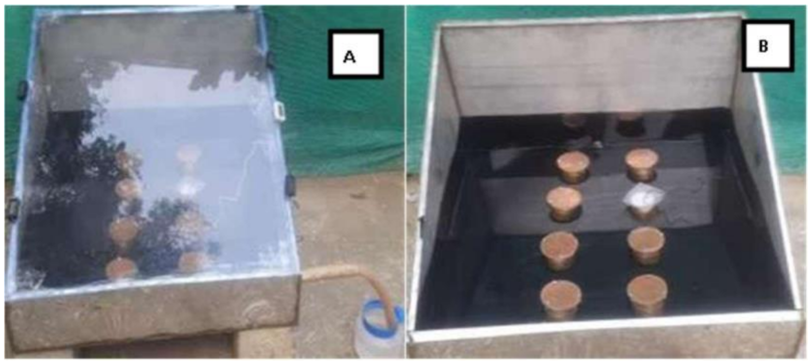


Figure 4 A and B Shows the photographic view of solar still

Table 4 Experimental variables

Variable	Symbols	Value
Latent heat of vaporization	L	2374(kJ/kg)
Density of water	ρ	988 (kg/m^3)
Air stream speed	v	1m/s
Angle of declination	δ	23^0
Latitude angle of Shahdol	φ	23.30^0

Table 5 Calibrated instruments used in measuring parameters with their precision and range

S.NO	Apparatus	Accuracy	Range
1	Solarimeter	05W/m^2	0-1499W/m^2
2	Wind speed meter	1-4	0.2-25m/s
3	Temperature sensor(PT-100)	±1^{o}C	-50-110^{o}C
4	Measuring jar	±05mL	200
5	Hygrometer (Ambient temperature)	±1^{o}C	-50 -70^{o}C

Chemical properties of water after distillation process

Figure 5 shows the water samples W1, W2, W3, and W4 being displayed after distillation, revealing that the water is clear and pure. After successfully removing impurities and contaminants Table 6 displays the chemical values of all four samples (W1, W2, W3, and W4) after the solar still experiment, conforming to the standards set by the BIS-10500 desirable limit.

Figure 5 Shows the photographic view of water samples W1,W2, W3, and W4 after distillation process

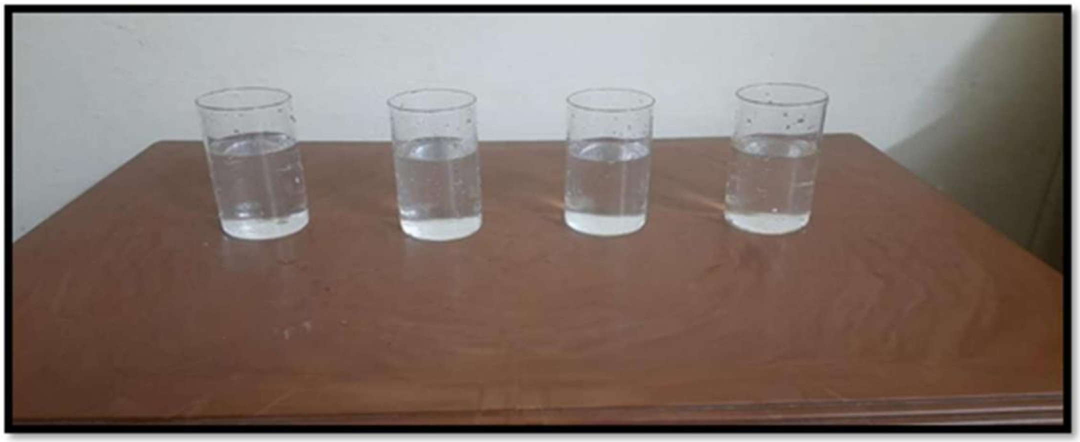


Table 6 shows the chemical parameters after distillation

Parameters	Solar stills			
	W1	W2	W3	W4
pH	7.0	6.5	6.9	7.5
Turbidity (NTU)	1	0.1	0.9	0.3
TDS mg/L	90	70	80	95
Total hardness mg/L	80	60	70	90
Total Alkalinity mg/L	90	55	65	110

Efficiency of solar still

The daily efficiency is produced as a result (still).The daily thermal efficiency of a solar still is calculated as follows:

$$\eta_{still} = \frac{M_d \times L}{\Sigma I \times A \times 3600} \quad (1)$$

Where,

Md = Hourly distillate output (kg)

L = Latent heat of vaporization (kJ/kg)

L = [2.4935 ×106(1-9.4779 × 10-4Tv+1.3132 ×10-7Tv2– 4.7974× 10-9Tv3)] for Tv < 700

I = Daily average radiation (W/ m2)

A = Area of glass cover (m2)

Uncertainty analysis

Equation (3) represents the formulation that Kline and McClintock [41] introduced. This equation is employed to assess uncertainties by taking into account the precision of mirrored parameters and properties utilized in the determination of the parameters (Y). The maximum uncertainty in measurements is determined to be approximately 2%.

$$\frac{\delta Y}{Y} = \sqrt{\left\{\frac{\delta X_1}{X_1}\right\}^2 + \left\{\frac{\delta X_2}{X_2}\right\}^2 + \text{-------} + \left\{\frac{\delta X_n}{X_n}\right\}^2} \quad (2)$$

Results and discussion

The hourly changes in ambient temperature and solar radiation

Hourly variations occur in the surrounding environment's temperature, the glass cover's temperature, and the sun's strength at May, the experiment was carried out in the latitude and longitude coordinates of 23.3002o, 81.3569o at Shahdol, Madhya Pradesh. Under constant weather circumstances, the three-solar-stills (SS, PCM, and NPCM) experiment has been run for four days in a row. The weather was stable over the course of the four days. As a result, the experiment was conducted while accounting for solar radiation and the average ambient temperature. This was done in order to reduce the experiment's reliance on weather and to ensure that the three solar stills produced reliable data. According to Figure 6 (A) and (B), which show solar radiation and ambient temperature, a hot weather season is in evidence in May when solar intensity reaches 1120 W/m2. The productivity of a solar still is increased with increasing solar intensity. In addition, the ambient temperature rises in May as a result of the higher temperature. The average variance in ambient temperature over time is shown in Figure 6 (B).

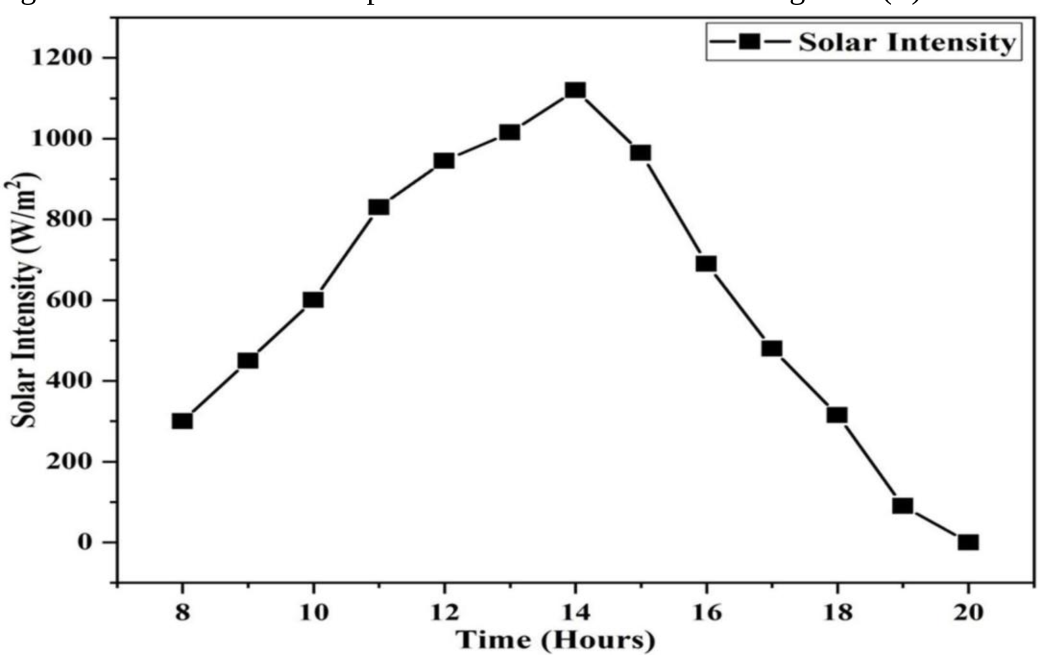


Figure 6 (A) Average solar intensity of SS, PCM and NPCM

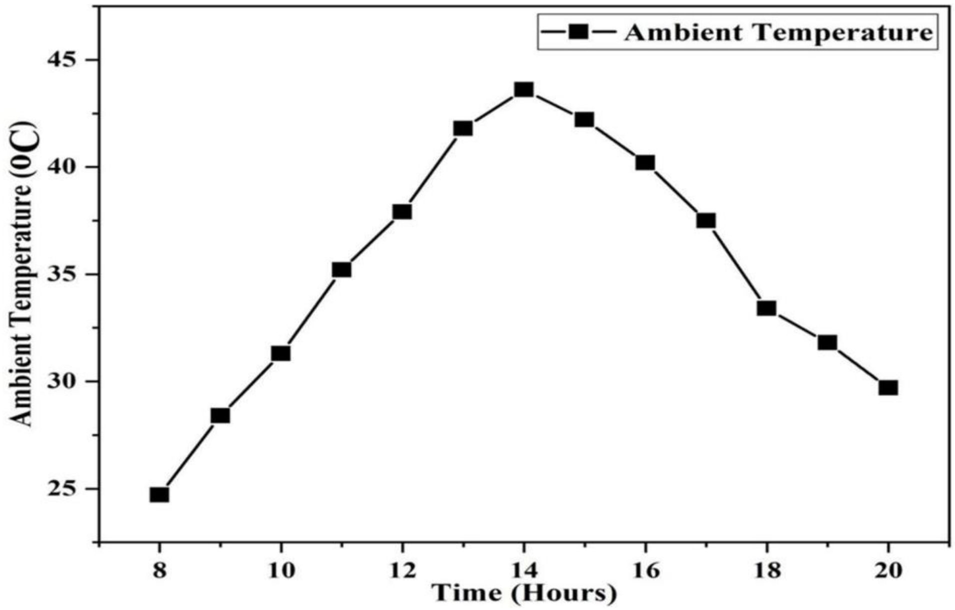


Figure 6 (B) Average ambient temperature of SS, PCM, and NPCM

The hourly fluctuation in water temperature.

Figure 7 (A, B, and C) shows the temperature fluctuation of the water with time. Water samples W1, W2, W3, and W4 were fed into each of the three solar stills simple solar still, solar still with PCM, and solar still with NPCM. The temporal fluctuations in water temperature are clearly seen in the illustrations. When comparing the observations for each sample in each solar still, noteworthy tendency emerges. The figures demonstrate that the peak temperatures of the three solar stills occurred between 2:00 pm. specifically, the simple solar still displays maximum water temperatures in the range of 61.10C, 63.20C, 62.50C, and 61.50C for all four samples W1, W2, W3, and W4. In contrast, solar still with PCM may attain maximum water temperatures of61.30C, 62.90C, 62.70C, and 610C at the same time intervals as the soar still with NPCM, which can reach maximum water temperatures of 61.90C, 63.80C, 62.9 0C and 61.50C.This pattern, which is the same for all three solar stills, highlights effectiveness and efficiency of the solar stills during the interval described earlier by displaying a peak in water temperature during that period.

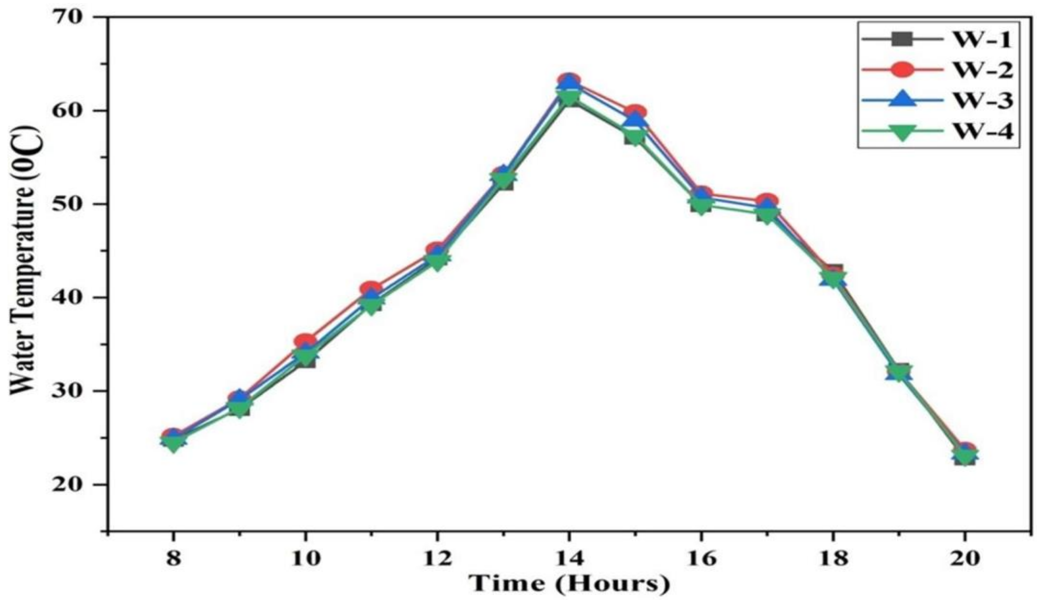


Figure 7 (A) Simple Solar still water temperature plot of sample number W1, W2, W3, and W4

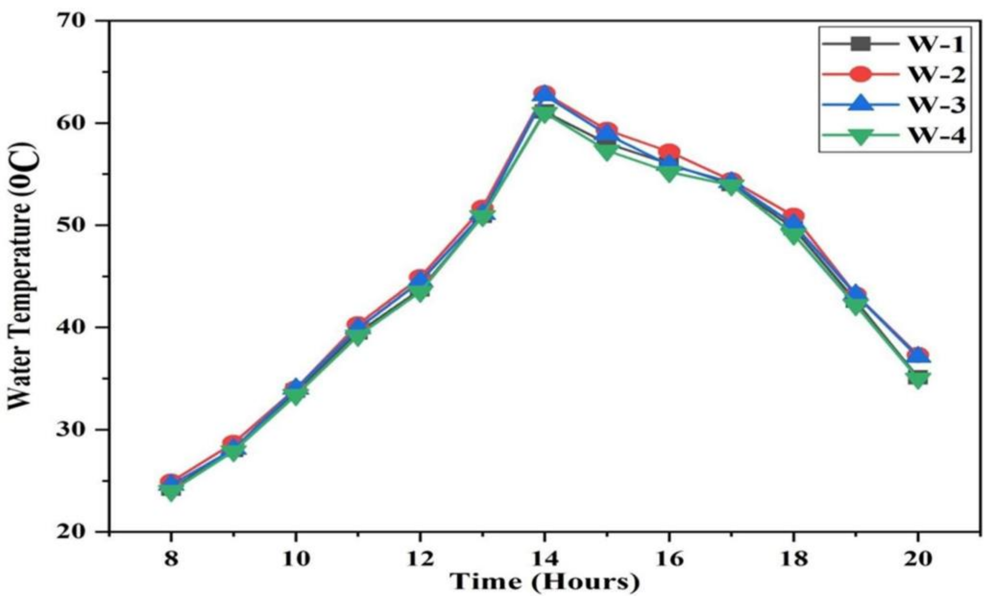


Figure 7 (B) Solar still with PCM water temperature plot of sample number W1, W2, W3, and W4

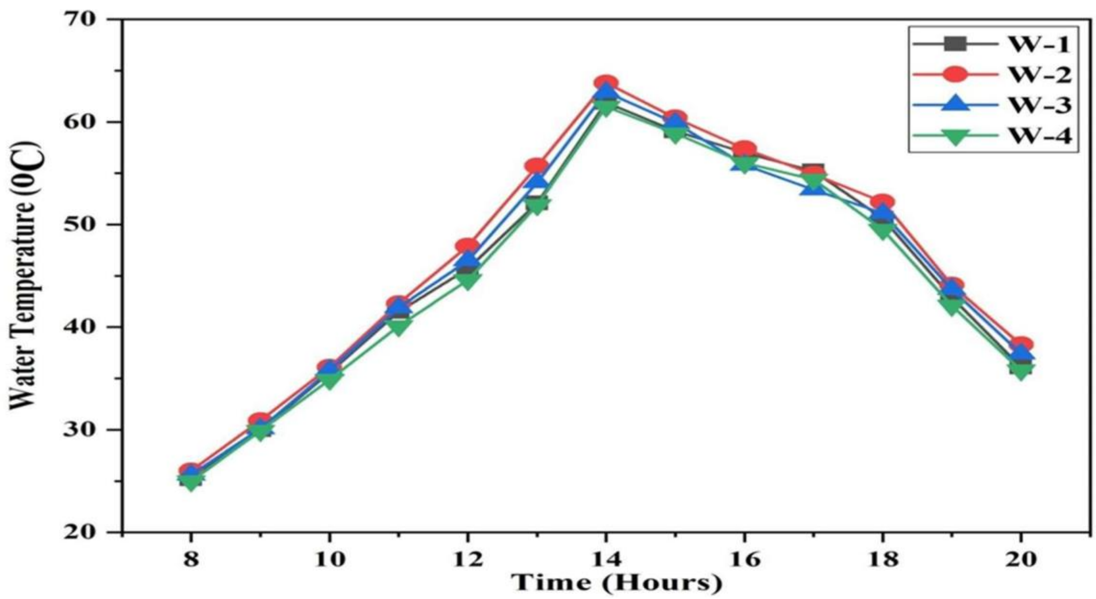


Figure7 (C) Solar still with NPCM water temperature plot of sample number W1, W2, W3, and W4

The hourly variation of glass covers temperature.

Figure 8 (A, B, and, C) shows the inner glass temperature fluctuation with respect to time. The variation shown separately for all three solar stills SS, PCM, and NPCM. Four samples of water W1, W2, W3, and W4 were tested in solar stills maximum glass temperature achieved at 2.00 PM. For SS maximum value of temperatures in the range of four samples W1, W2, W3 andW4 are 64.80C, 65.20C, 650C and 64.40C. In contrast, solar still with PCM may attain maximum glass temperatures of 690C, 69.80C, 69.30C, and, 68.90C at the same time intervals as the solar still with NPCM, which can reach maximum glass temperatures of 69.10C, 69.90C, 69.40C and, 690C.

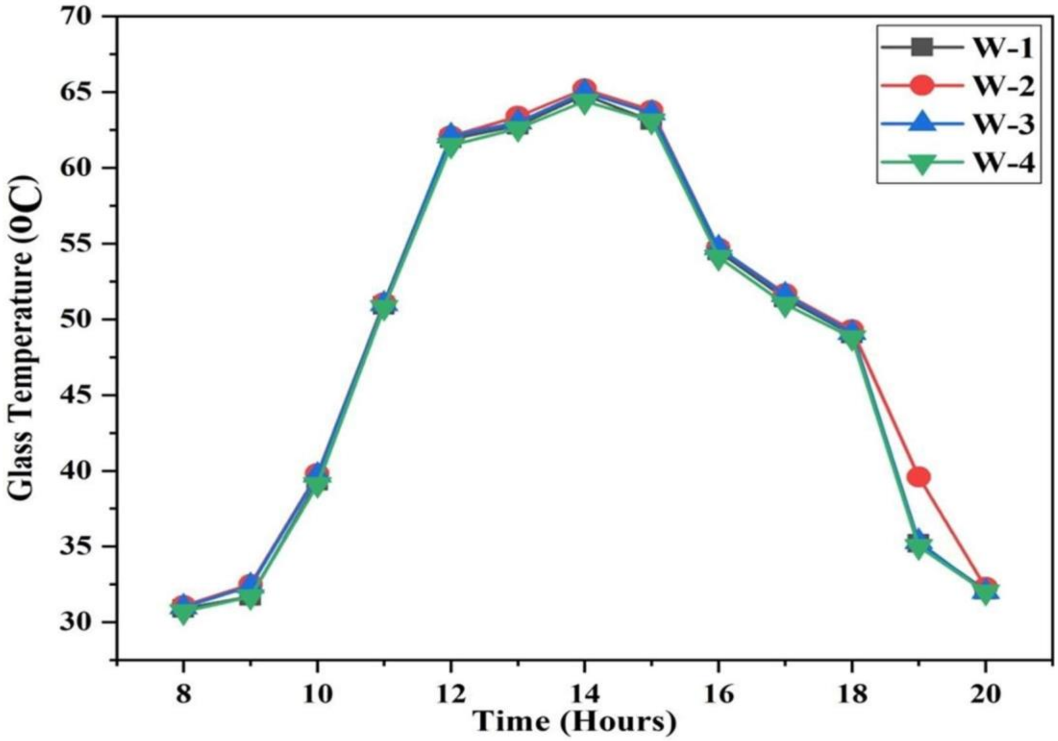


Figure 8 (A) Simple Solar still glass cover temperature plot of sample number W1, W2, W3, and W4

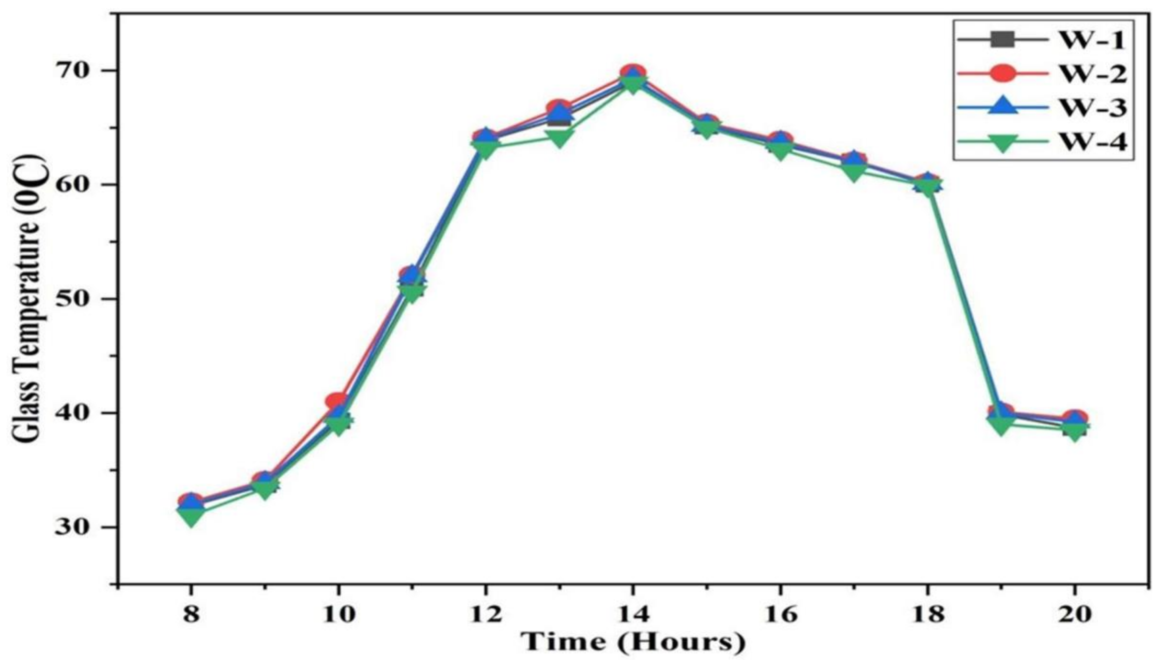


Figure 8 (B) Solar still with PCM glass cover temperature plot of sample number W1, W2, W3, and W4

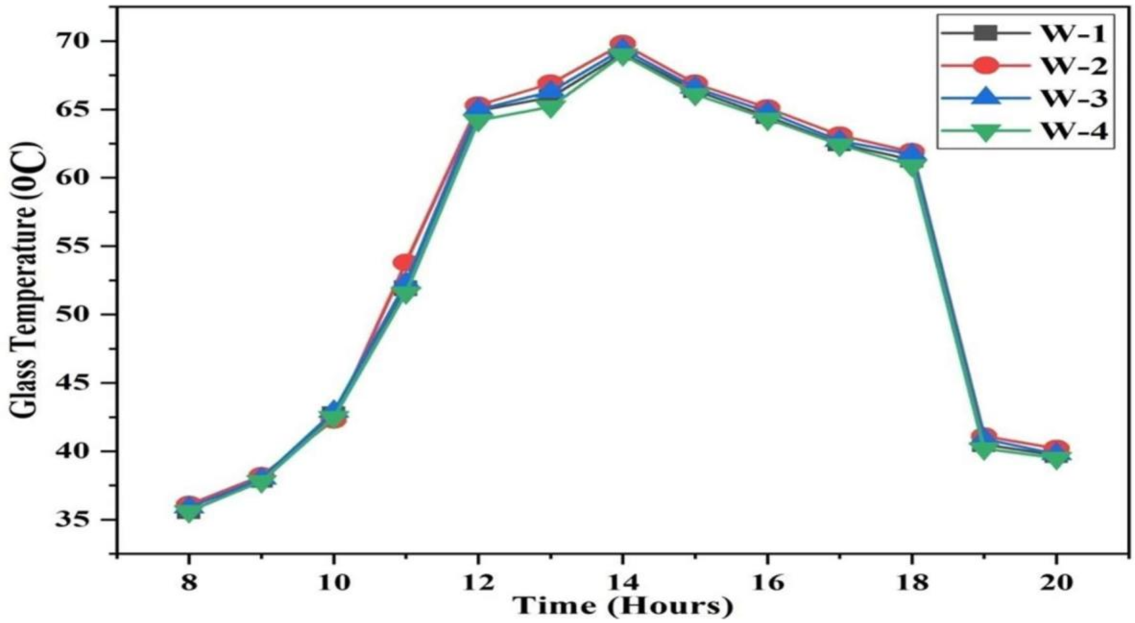


Figure 8 (C) Solar still with NPCM glass cover temperature plot of sample numberW1, W2, W3, and W4

Distillate output of four samples

Figures 9 (A, B and C) illustrate the hourly distillation performance of solar stills for four samples, W1, W2, W3, and W4. The maximum productivity observed around 2.00 PM across all solar stills. This clear evidence from real life shows that adding PCM and nanoparticles to solar stills increases the distillation yield, even when the sun's radiation isn't at its best. After the experiments for samples W1, W2, W3, and W4, the results reveal productivity of 1800 ml/m2day, 1997 ml/m2 day, 1887 ml/m2 day, and 1735 ml/m2 day, respectively, for the SS system. Simultaneously, the PCM system exhibits distillate output of 2695 ml/m2 day, 3025 ml/m2 day, 2830ml/m2 day, and 2380ml/m2 day for the same samples. Notably, the NPCM system demonstrates superior performance, yielding distillations of 3250 ml/m2 day, 4305 ml/m2 day, 3510 ml/m2 day, and 2860 ml/m2 day for samples W1, W2, W3, and W4. After the distillation trials were conducted, it was clear that the maximum distillation occurred in the W2 sample, surpassing the output of all three solar still systems. This observation implies that W2 is tap water with minimal contamination, leading to increased distillate production across all water samples. The reduced contamination levels contribute to a higher evaporation rate, resulting in greater distillation output [42, 43].

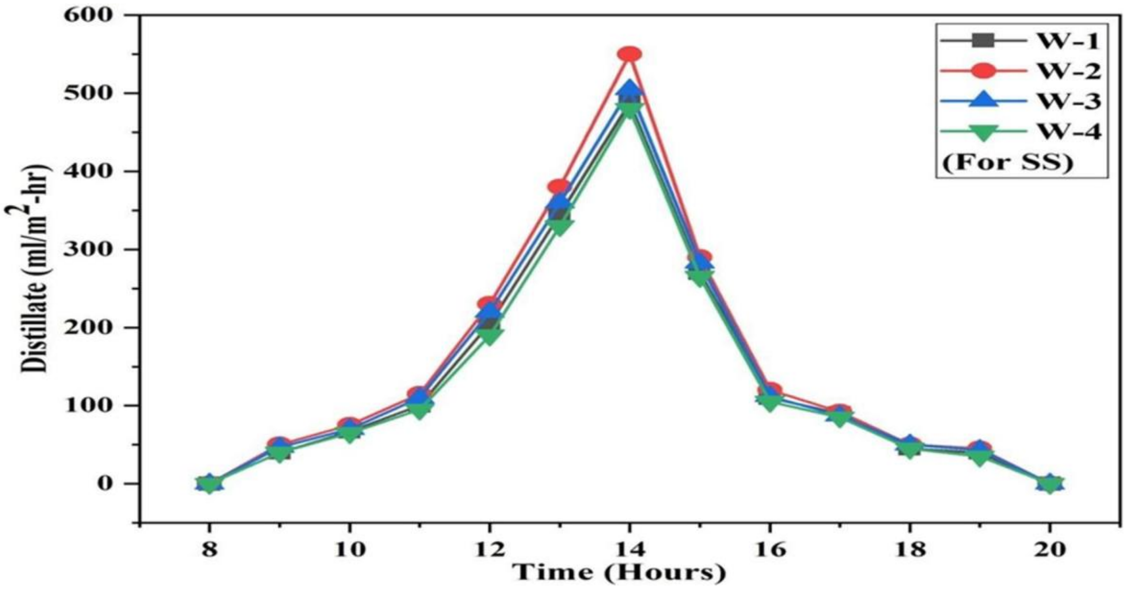


Figure 9 (A) Simple solar still distillation plot of sample number W1, W2, W3, and W4

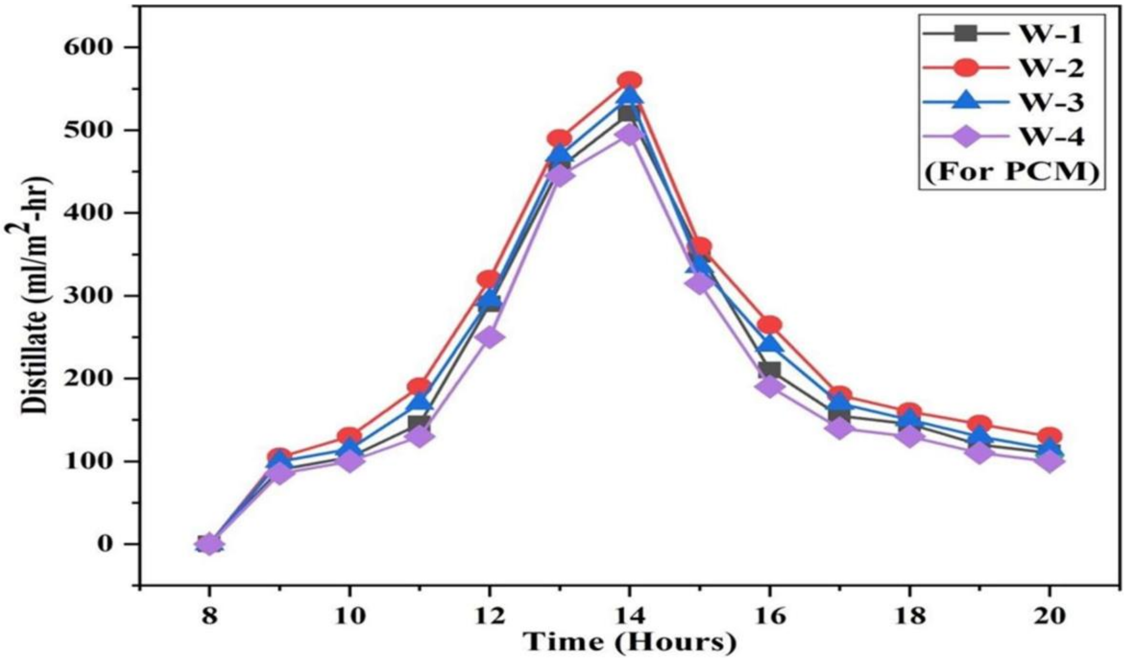


Figure 9 (B) Solar still with PCM distillation plot of sample number W1, W2, W3, and W4

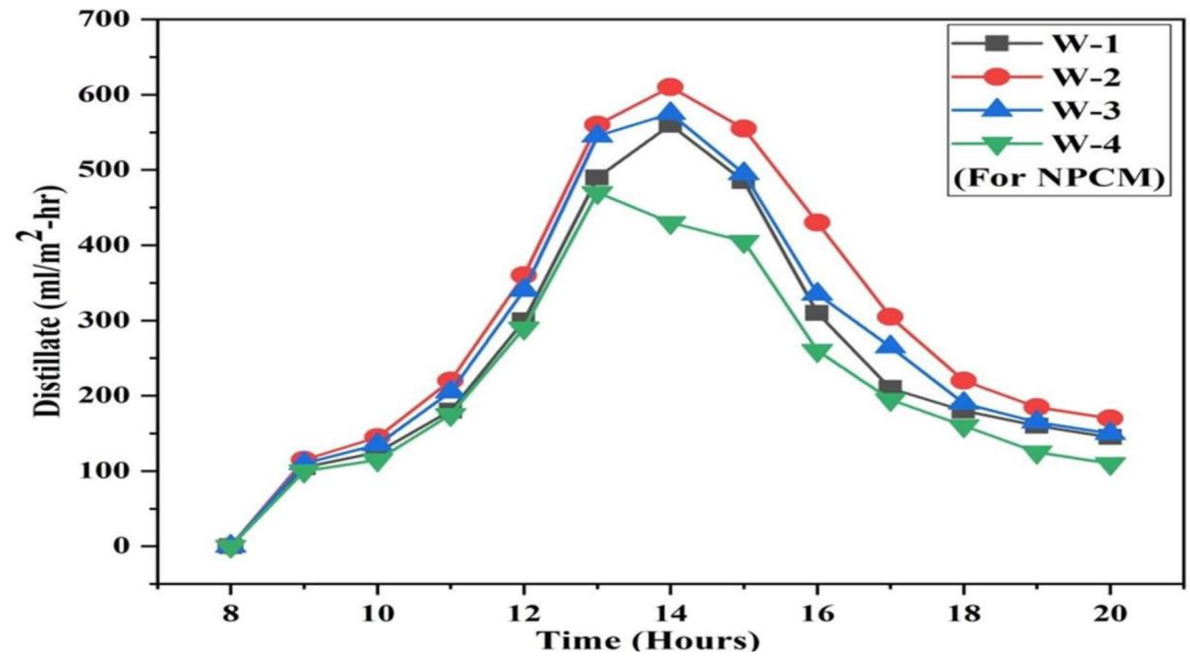


Figure 9 (C) Solar still with NPCM distillation plot of sample number W1, W2, W3, and W4

Conclusions and future scope

- Incorporating petroleum jelly with copper oxide nanoparticles significantly boosts productivity by 40% compared to a simple solar still.
- The NPCM system demonstrated superior efficiency in fresh water generation as compared with other systems SS and PCM that were examined.
- The solar still proves to be an excellent distillation system for purifying contaminated water, utilizing solar energy for the water purification process.
- The results reveal productivity of 1800 ml/m2 day, 1997 ml/m2 day, 1887 ml/m2 day, and 1735 ml/m2 day, respectively, for the SS system. Simultaneously, the PCM system exhibits distillate output of 2695 ml/m2 day, 3025 ml/m2 day, 2830 ml/m2 day, and 2380ml/m2 day for the same samples .Notably, the NPCM system demonstrates superior performance, yielding distillations of 3250 ml/m2 day, 4305 ml/m2 day, 3510 ml/m2 day, and2860ml/m2day for samples W1, W2, W3,and W4.
- Evaporation process is less effective due to the high concentration of pollutants that reduce the vapor pressure and transmissibility of solar radiations.
- Modeling a solar still is a worthwhile project with bright future possibilities. By simulating the complex processes of solar energy absorption, heat transmission, and evaporation, solar still simulations can be used to maximize their efficiency.

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