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Original Research

A Modified Solar Still with Geopolymer Material as Heat Source

Z. K. Khudair [1], Ali A. F. Al-Hamadani [2], Imad Ali Disher [3], Shailendra Kumar Shukla [4]

[1,2] Mechanical Engineering Department, College of Engineering, Wasit University, Kut, Iraq.
[3] Department of Ceramics and Building Materials, College of Materials Engineering, University of Babylon, Babil, Iraq.
[4] Department of Mechanical Engineering, Indian Institute of Technology BHU, Varanasi 221005, India

Corresponding Author Email: Std202303.Z.K@uowasit.edu.iq

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ABSTRACT

This work is an experimental study of a single-basin, inclined glass solar still using a ceramic material as the storage medium. The geopolymer–graphite ceramic material functioned as an internally electrically heated thermal storage element, operating at 12V and with an electrical input power ranging from 15 to 29 W during the experiments. The material is environmentally friendly and operates at a low voltage, making it suitable for use with sustainable energy sources. The study was conducted under the climatic conditions of Wasit (32.516°N, 45.846°E) on specific days to investigate the effect of the ceramic material on the still's daily productivity and efficiency. Two samples of the ceramic material were prepared. The first sample consisted of three separate ceramic samples that were packaged and placed inside the still, while the second sample was a large, processed sample placed at the base of the still. The modified solar still achieved a freshwater productivity of 2.20 L/m²·day compared with 1.67 L/m²·day for the conventional solar still, corresponding to an enhancement of approximately 31.7 %. Furthermore, the thermal efficiency of the modified solar stills with the ceramic material reached 45%.

Keywords: Water desalination, Glass solar still, Single-slope solar still, Geopolymer–graphite ceramic material.

1. Introduction

It Since water is necessary for all biological activities, it is the primary source of life on Earth. Water has a stabilizing impact on earthly and interplanetary processes due to its abundance and physicochemical properties [1]. Just 3% of the water on Earth comes from freshwater sources; the rest, 97%, is saline [2]. However, around 2 billion people do not have access to clean, safe water [3]. Solar distillation provides an easy way to make thermal processes that are typical of the hydrological cycle on Earth that can be utilized to create potable water to satisfy the need for drinking water in rural households [4]. Solar distillation uses clean and free solar energy and is classified into direct and indirect methods. Direct systems use solar stills or humidification-dehumidification, while indirect systems rely on photovoltaic panels or solar collectors [5]. Several methods have been developed to increase the productivity of solar stills; these methods are often divided into passive and active improvements. Wick materials, phase-change materials, fins, reflectors, and glass-cover cooling are examples of passive improvements; in contrast, active systems use external energy sources like solar collectors and photovoltaic-powered heaters to increase freshwater production and provide extra thermal energy [5]. A passive solar still with an external condenser produces 62% more distillate than a traditional one. Increasing the glass-cover area or reducing its temperature further boosts distillate production [6]. A solar still uses solar heat to evaporate and condense water, offering a low-cost and eco-friendly option for remote areas. Research has focused on improving its design and efficiency through new geometries, materials, reflectors, nanofluids, and thermal storage [7].
Researchers are working to increase the productivity of solar stills because the 2–5 L/m²/day produced by conventional systems is insufficient for individual needs [8]. Consequently, to achieve a freshwater yield above 5 L/m²/day, either larger areas or design changes are needed [9].

One of the most significant modern modifications, using various wick materials, significantly boosts evaporation in solar stills, with some systems showing up to a 180% increase in freshwater productivity [10]. A new solar still design using phase-change material and added fins enhances heat transfer and daily yield, increasing water production by 46%, 48%, and 52% for finned, finned-pond, and combined systems, respectively [11]. Reflectors and sun-tracking systems enhance solar absorption, with internal reflectors raising daily yield and efficiency by up to 75% and 56%, and sun-tracking support increasing yield by up to 22% [12]. Freshwater yield rose by 370% when a 350-W DC water heater was used, whereas an external cooling fan reduced productivity by 7% and 15% at wind speeds of 7 and 9 m/s, respectively [13].

Numerous investigations have been conducted over the years with different basin materials. Experiments with a Plexiglas still found that the maximum distilled output is 2.1 L/m²/day at a water depth of 2 cm in a still basin [14]. A lauric-acid PCM solar still showed major gains, increasing productivity by 127% at night and 30–35% by day. Higher PCM mass and lower water mass improved performance, with inner glass temperature giving better predictions [15]. This research aims to improve the performance of a simple solar still using geopolymer material. Thanks to its low thermal conductivity, this material reduces heat loss across the base and sides, efficiently insulates the heating element, and prevents any interference with the water. Furthermore, it promotes more uniform heat distribution within the still, resulting in higher water temperature and a higher daily evaporation rate, thus improving the still's thermal efficiency and overall productivity.

Passive improvement methods such as wick materials, glass cover cooling, reflectors, and thermal energy storage materials have been the main focus of recent research on solar desalination systems. To increase evaporation rates and freshwater productivity, other studies used active systems driven by photovoltaic modules or external electrical heaters. The application of electrically self-heating geopolymer–graphite ceramics material as combined thermal storage and internal heating elements inside small solar stills has, however, received little attention. Therefore, more experimental research is needed to assess the effectiveness of these materials' work to improve freshwater production, evaporation rate, and water temperature dispersion.

This study aims to examine the performance of a solar still with a low-voltage geopolymer-graphite compared to that of a standard solar still under similar operating conditions.

The current study can be improved by integrating a low-voltage geopolymer-graphite ceramic material inside the basin of a solar still, which is expected to improve the saline water temperature profile, enhance evaporation and condensation, and ultimately increase freshwater productivity and thermal efficiency.

2. Materials and experimental setup

The simple solar still was designed entirely of glass, taking advantage of glass's resistance to rust from frequent use of brine and its ease of continuous cleaning. It features a (30 × 30) cm base, a 20 cm front wall, and a 37.3 cm back wall with a 30° incline, as shown in Fig. 1. The traditional solar still was modified to incorporate geopolymer-graphite ceramic material into the system, improving purified water production. The glass thickness for the base and walls is 6 mm, and the glass cover is 4 mm. An additional wooden model, measuring (37×35) cm and 2 cm thick, was also constructed and lined with thermal wool to minimize heat loss and provide a more secure appearance to the glass solar still.

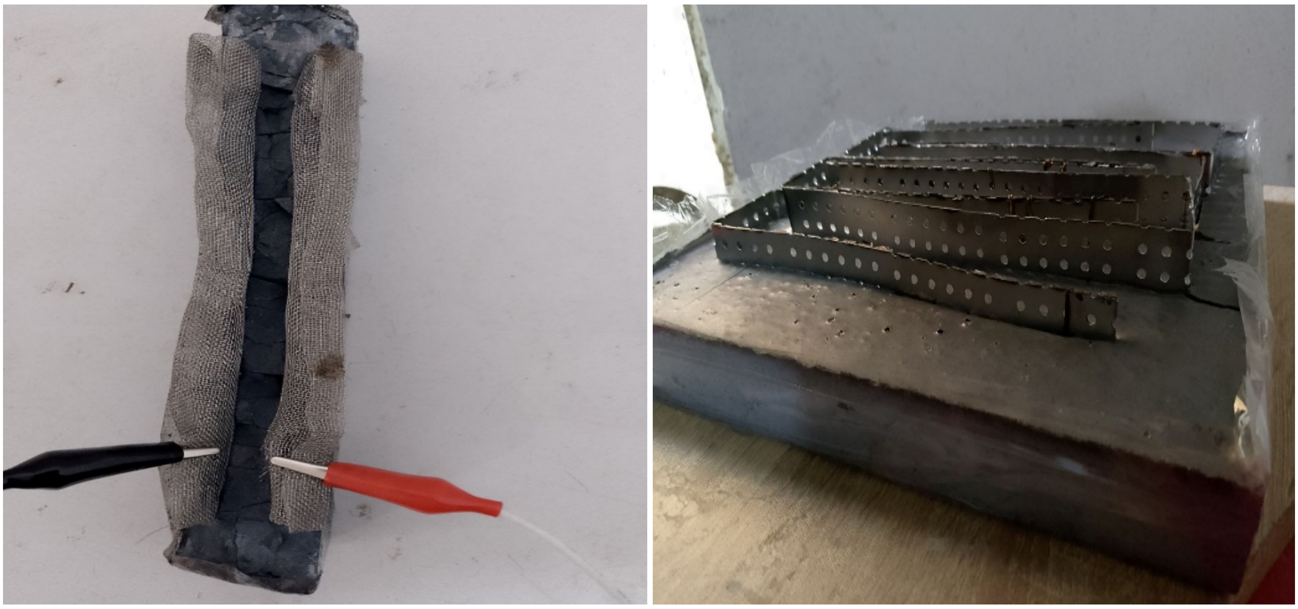
Figure 1. Single-slope glass solar still used in the experiments

As for the material, it is a type of geopolymer–graphite ceramic that generates heat when supplied with low-voltage electricity, not exceeding 12 volts. The material was manufactured in the laboratories of the University of Babylon using a base material called geopolymer with the addition of graphite.

Promising self-heating smart materials with a high graphite content are graphite/geopolymer composites.

Compressive strength at various ages and performance under AC and DC voltages were among the physical, mechanical, electrical, and thermoelectric characteristics that were assessed. The electrodes are pre-supplied with wires connected to the unit. They can be connected directly to standard wires. It can be powered by direct current (DC). The voltage range is from 6 to 12 volts. Two ceramic samples were made. The first sample (CR1) has dimensions of (23.5×4×3.5) cm as shown in Fig. 2(a), and the second sample (CR2) has dimensions of (24×24×3) cm as shown in Fig. 2(b).

According to the study, electrode–sample barrier development is what causes electrothermal deterioration, which can be lessened by washing to get rid of free ions. Its promise for intelligent, anti-freezing building materials was demonstrated by the achievement of a composite with 47 MPa strength and stable self-heating at 98 °C [16].



(a) (b)

Figure 2. Geopolymer–graphite ceramic material samples used: (a) CR1 and (b) CR2.

The first model was encased in stainless steel, as shown in Fig. 3, and electrically insulated in preparation for being placed in water. The purpose of the packaging is to protect the material from water, but it's essential to insulate the material electrically from the packaging material by placing spacers between them in the form of supports to prevent thermal insulation. The packaging material can be any metal, as long as it doesn't corrode during the testing period. Aluminium (Fabron) is an excellent choice. It needs to be secured inside the mould with electrically insulating supports. The support needs to withstand the generated heat. Galvanised iron, stainless steel, or aluminium can be used to prevent corrosion. The important thing is to use a metal that ensures higher thermal conductivity. The geopolymer–graphite ceramic material was encased in stainless steel and insulated with refractory clay because the ceramic material didn't adhere properly, resulting in a resistance of 0.7. It was insulated from below with refractory clay and from above with thermal insulation, cardboard, and two types of thermal silicone. The electrical insulation mustn't also provide thermal insulation, as shown in Fig. 3, in the packaging stages.

Figure 3. Stages of packaging and insulation of (CR1)

2.1. Electrical characteristics of the geopolymer material

The electrical power supplied to the material was calculated using:

1. Electrical Power:

$$P = V * I \quad (1)$$

Where:
P = electrical power (W)
V = supplied voltage (V)
I = electrical current (A)

2. Electrical Energy Input:

$$E_{elec} = P * t \quad (2)$$

Where: E_{elec}: is electrical energy input (Wh) and t: is operating time (h)

$$\eta = \frac{m*h\_fg}{(A*I*t)+E_{elec}} * 100 \quad (3)$$

where η is the overall thermal efficiency (%), m is the mass of distilled water produced (kg), hfg is the latent heat of vaporization of water (kJ/kg), A is the basin area (m²), I is the average solar irradiance (W/m²), t is the exposure time (hours), and E_{elec} is the electrical energy supplied to the material during the experiment. The electrical measurements were recorded both after encapsulation and during actual operation inside the solar still to reflect realistic operating conditions and quantify thermal losses due to insulation and heat transfer within the basin. See Table 1.

Table 1. Electrical and Thermal Operating Characteristics of the Geopolymer–Graphite Ceramic material Samples (CR1 and CR2)

Parameter	CR1	CR2
Operating voltage (V)	11.1	10.35
Average current (A)	1.35	2.80
Average electrical power (W)	15	29
Maximum material temperature (°C)	98	65
Average material temperature (°C)	74	49
Operating duration (h/day)	8	8
Daily electrical energy input (Wh/day)	120	232

3. Experimental procedure

The experiments were conducted in Al-Kut on separate days in September and October 2025. And experimental data were recorded every 30 minutes between 9:00 AM and 4:00 PM. An indoor experiment using an electrically heated geopolymer–graphite ceramic material and an outdoor experiment under natural solar radiation were performed. Throughout all experiments, the basin water depth remained constant at 1,2, and 3 cm. The solar still's glass cover was angled south to enhance solar radiation absorption in the climatic conditions of Wasit, Iraq. The system was oriented north-south to maximise solar radiation exposure on the test days. Temperatures were recorded throughout the solar stills.

The geopolymer–graphite ceramic material was used in experiments with low-voltage DC settings (6–12 V). Throughout the modified solar still studies, the material was continuously operated from 9:00 AM to 4:00 PM and exhibited steady thermal performance at 12 V. Low-voltage operation facilitated interoperability with sustainable electrical energy sources such as photovoltaic systems and enhanced operating safety. The ceramic material's constant heating helped to keep basin water temperatures higher and improve the solar still's evaporation process. Fig. 4 represents the ceramic material installed inside the basin of the solar still.

The temperatures of the glass, brine, and geopolymer–graphite ceramic material were measured. An Arduino was used, and its electronic components were tested and calibrated before use. Total solar irradiance was measured on a horizontal surface using a Kipp and Zonen solar irradiometer with a sensitivity of 15.53 µV/W/m² (during outdoor experiments under natural solar radiation). Calibrated K-type thermocouples, connected to a digital thermometer, were used to measure the temperature of the ceramic samples. See Fig. 5 and 6.

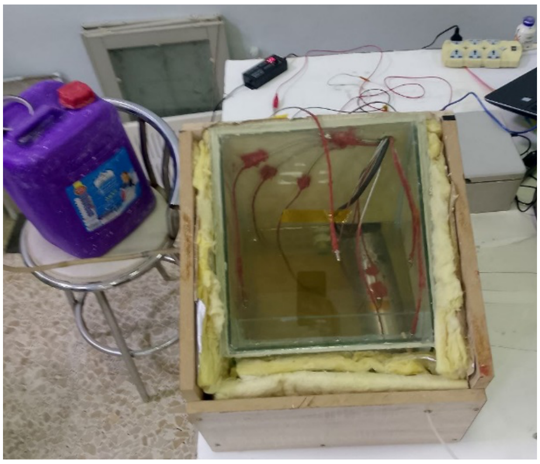


Figure 4. The ceramic material (CR1) is installed inside the basin of the solar still

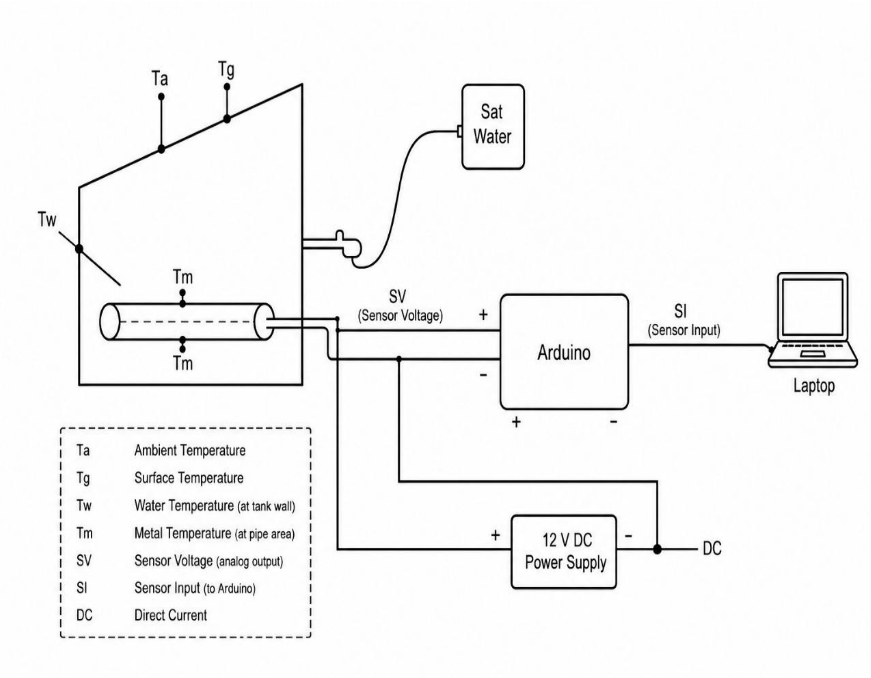


Figure 5. Schematic diagram of the experimental setup for temperature monitoring and data acquisition in the solar still system.

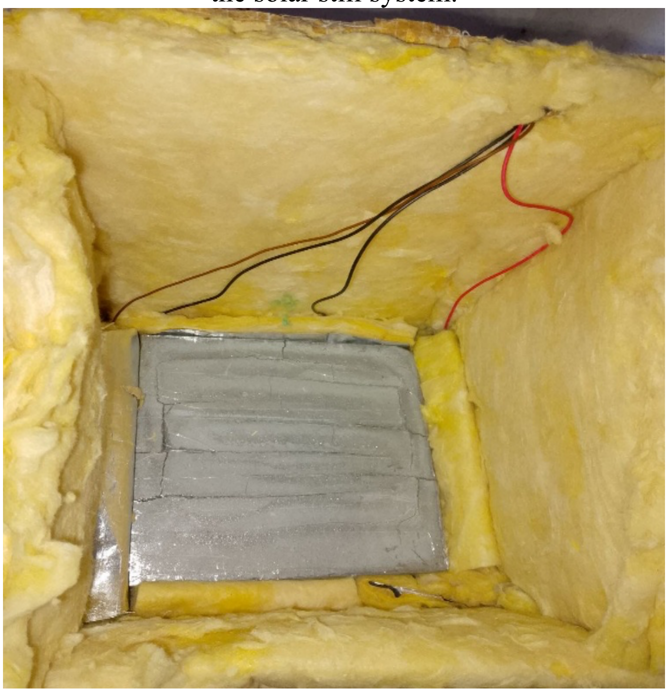


Figure 6. The ceramic material (CR2) is placed beneath the basin of the solar still.

4. Feed water characteristics

Raw water samples were sourced from a lake in the Al-Nu'maniya District, Wasit, Iraq, on July 30, 2025, for use in the solar distillation process. A physical and chemical analysis of the sample was conducted, and the results revealed that the turbidity and pH were within acceptable limits. Nevertheless, the salinity was very high, making it unsuitable for direct use, as shown in Table 2.
Fig. 7 illustrates the sampling location for the saline water sample.

Figure 7. Location of the feed water collection site in Al-Nu'maniyah district, Wasit, Iraq.

4.1. Physical and Chemical Tests of Feed Water

The tests were done on the saltwater sample since the salinity level was very high. Therefore, the water is unsuitable for direct use and requires appropriate treatment to reduce the salt concentration and improve its quality, where TDS before treatment was 9218 mg/L. The desalination process reduced the total dissolved solids (TDS) concentration of the feed water to approximately 140 mg/L, indicating acceptable drinking water quality according to WHO recommendations.

Table 2. Results of physical and chemical tests of feed water

Parameter	Raw	MPL
Turbidity, NTU	4.03	5
Temperature, °C	30.9	ACC.
pH	7.5	6.5–8.5
E.C., µS/cm at 25°C	12290	2000
Alkalinity (as $CaCO_3$)	/	/
Hardness (as $CaCO_3$)	/	500
Calcium (as Ca)	/	150
Magnesium (as Mg)	/	100
Chloride (as Cl)	/	350
Aluminum (as Al)	/	/
Sulphates (as SO_4)	/	400
Sodium (as Na)	/	200
Potassium (as K)	/	/
T.D.S.	9218	1000

5. Results and discussions

The ceramic material was tested before and after packaging, under similar atmospheric conditions, to ensure the accuracy of the measured results. Fig. 8 shows the pre-coating temperatures of one of the ceramic samples. Pre-coating temperatures were measured at multiple locations above and below the ceramic material. Temperature measurements at T_1 and T_2 were at the top of the ceramic material, while T_3 and T_4 were at the bottom. Temperatures at T_3 and T_4 were significantly higher than at T_1 and T_2, reaching an average of 105°C at T_3 and T_4 over 2 hours, and the difference between them was three or four degrees, compared to 74°C at T_1 and T_2. After curing, temperatures decreased considerably, with T3 and T4 reaching an average of 76°C; as for T_1 and T_2, it was 42°C over 2 hours. This decrease is attributed to the fact that the temperature below the ceramic material was significantly higher than the temperature above it, by approximately 20°C. These temperature variations differed from one sample to another.
After packaging, as mentioned previously, the temperature decreased by approximately 25°C, depending on the temperature difference for each sample, as illustrated in Figs 8 and 9.

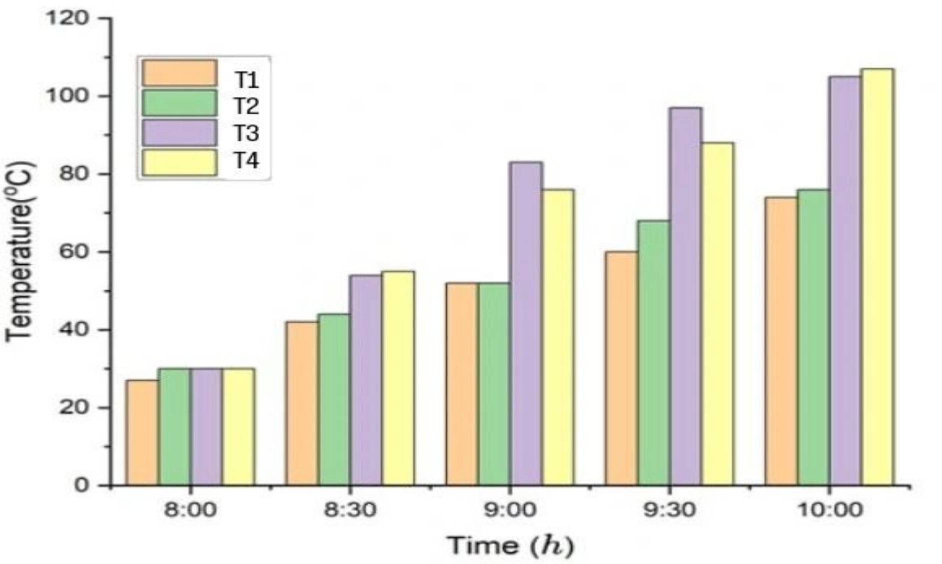


Figure 8. Temperature distribution of the geopolymer ceramic material before packaging

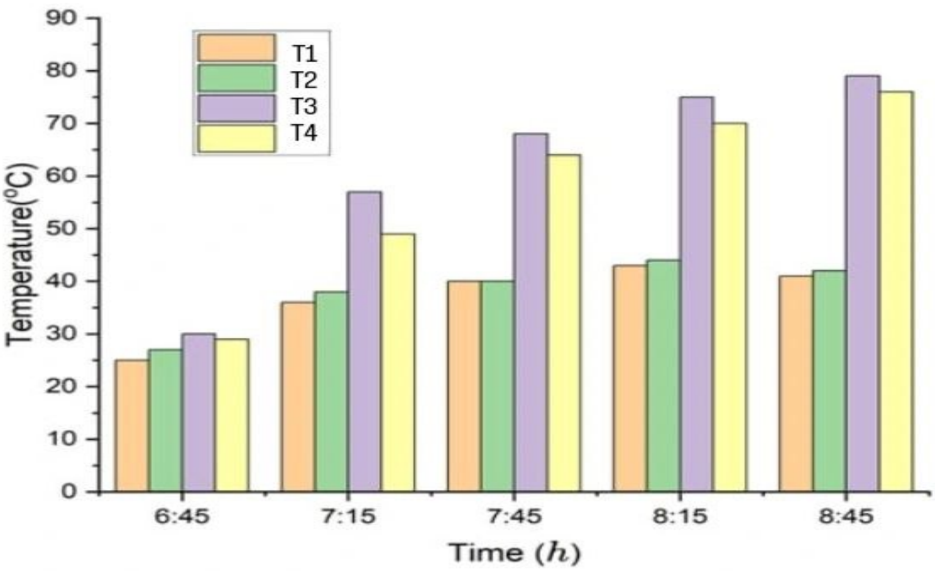


Figure 9. Temperature distribution of the geopolymer ceramic material after packaging

Fig. 10 illustrates the operational performance of the solar still integrated with a geopolymer ceramic material (SDWC), where T_m, T_w, T_g, and T_a denote the temperatures of the ceramic material, basin water, glass cover, and ambient air, respectively. The operation of the conventional solar distillation (CSD) system within a laboratory environment. A notable temperature gradient is observed between the laboratory setup (Fig. 10) and the outdoor conditions (Fig. 11). In both configurations, the monitored temperatures exhibit significant variations. The ceramic material's thermal output and its function in raising the water's temperature are the main causes of this discrepancy. This enhanced temperature differential facilitates vapor condensation on the tilted glass cover, thereby optimizing the overall productivity of the solar still during the laboratory experiments.

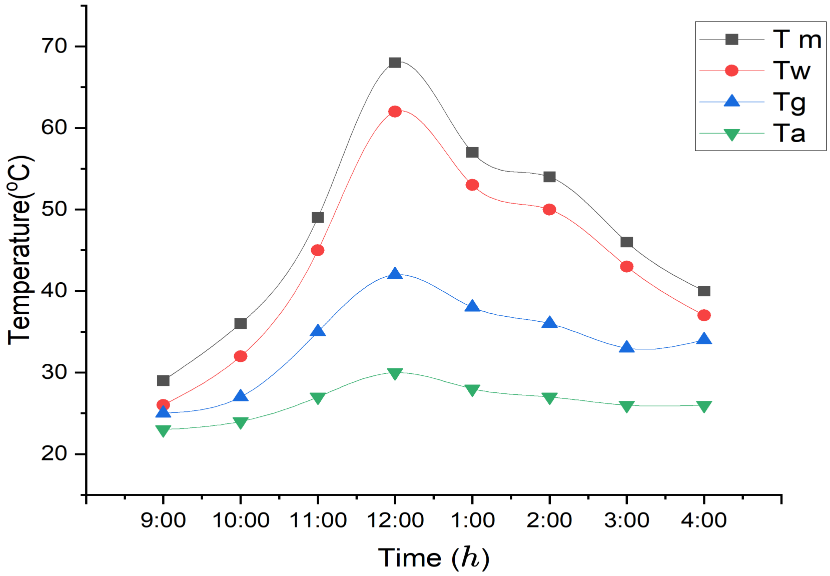


Figure 10. Temperature variations of the modified solar still with geopolymer ceramic material (SDWC)

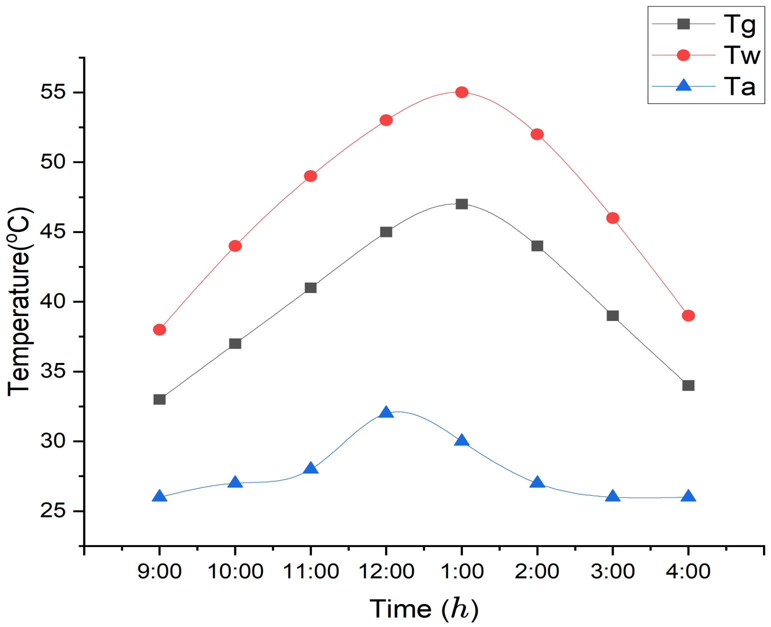


Figure 11.Temperature variations of the conventional solar still (CSD) inside the laboratory

On October 9th, 10th, and 11th, the solar still was operated outside the laboratory using only irradiant water heating to determine the actual productivity. Fig. 12 illustrates the variations in irradiance intensity, which were similar throughout the experiment, reaching their peak at midday before gradually declining.

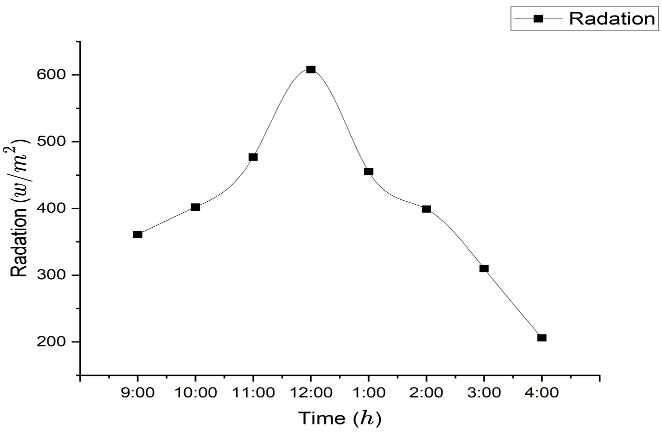


Figure 12.Variation of solar irradiance intensity during the experimental day for CSD.

Fig. 13 illustrates the hourly production rate of fresh distilled water from both a solar still with a ceramic coating and a conventional still. Fresh water was collected for 8 hours, with peak production occurring at 12:00 PM, followed by a gradual decline. The fresh water production from the SDWC is significantly higher than that of the conventional still. This is attributed to the lower solar radiation received by the brine in the still's tank, which in turn reduces evaporation. Furthermore, the ceramic coating plays a crucial role in raising the water temperature beyond the average irradiance, and the controlled internal conditions within the laboratory contribute to increased production.

In small-scale solar stills, the thermal behavior exhibits considerable variations between laboratory operation utilizing an internal heat source and external operation, relying on solar radiation. In the former, the water temperature surpasses the glass temperature due to direct internal heating. Conversely, in the latter, the glass cover becomes hotter due to direct exposure to solar irradiance. This shift in the temperature gradient directly affects the evaporation mechanism and production values

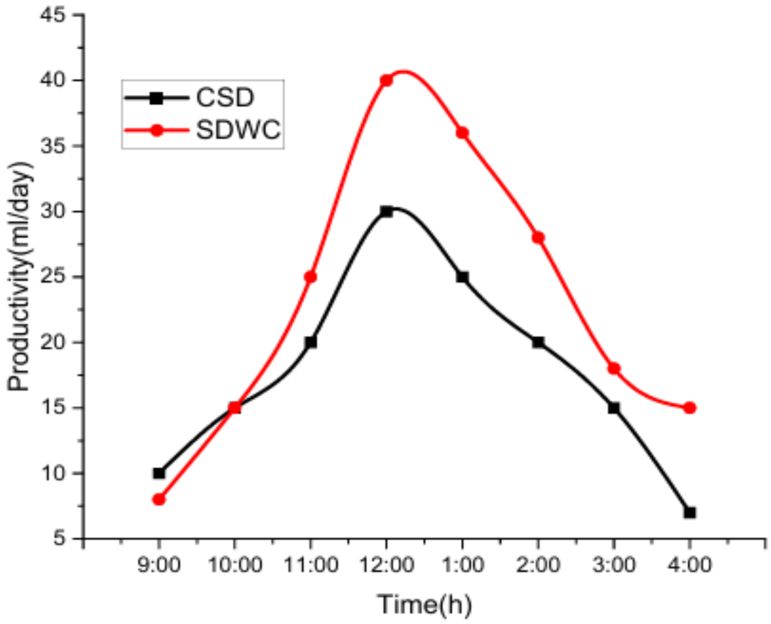


Figure 13. Hourly freshwater productivity of the conventional CSD and modified SDWC solar stills.

The comparison presented in this study aimed to evaluate the potential contribution of the geopolymer material under controlled operating conditions. Since the modified and conventional systems were tested under different heat input conditions, the reported increase in productivity should be interpreted as an

indicator of improved performance rather than a direct one-to-one comparison under the same environmental conditions. The ceramic material of the solar still increases the device's productivity by 31.7% compared to a conventional solar still. Volumetric Thermal Efficiency (VTE) was identified as the critical evaluation factor for ideal device performance. Fig. 14 displays the variations in VTE under typical atmospheric conditions. The conventional one still had a lower VTE than the solar one, which was still made of ceramic. The higher temperature of the ceramic material and the laboratory setting may be causing this elevated water temperature. Due to reduced evaporation, increased solar radiation, and the tank's saline water being at a higher temperature, VTE was lower in the morning. Figure 14 illustrates the average hourly performance of the solar stills using the ceramic material during the experimental period. The results show that the productivity and thermal efficiency of a solar distillation device are directly related. The researchers reached a similar conclusion [17].
The VTE of the solar still was calculated to evaluate the thermal performance of the desalination process. The instantaneous thermal efficiency was determined using the following equation:

$$\eta_i = \frac{m^{\cdot} * h_{fg}}{A * \mathrm{I}} \quad (4)$$

where η_i is the instantaneous thermal efficiency, ṁ is the distillate productivity rate (kg/s), hfg is the latent heat of vaporization of water (J/kg), A is the basin area (m²), and I is the solar irradiance intensity (W/m²).

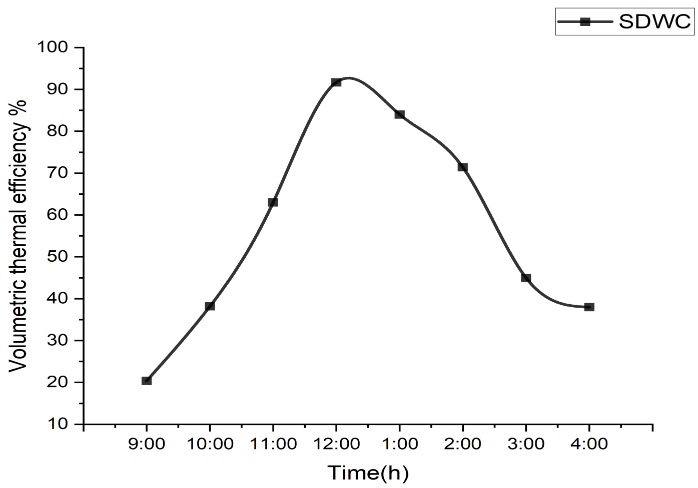


Figure 14. Variation of volumetric thermal efficiency (VTE) of the modified solar still during the experimental period

6. Conclusions

A self-heating geopolymer material, powered by sustainable energy sources, was used in a pilot study with a solar still. The material, which operates at low voltage, was used in conjunction with stainless steel-coated ceramics and other ceramics of varying sizes. The distillation results of these materials were studied and compared. For a 30 × 30 cm base solar still, distillation using the ceramic material (CR2) yielded a total distillate production of 2.20 L/m²·day when the solar still was integrated with the self-heating geopolymer material under laboratory conditions. Under solar irradiance, the conventional solar still produced 1.67 L/m²·day using solar energy alone. Results showed that the solar still equipped with the self-heating material achieved a 31.7% increase in distillation yield compared with the conventional solar still.
High processing efficiency can be achieved through the treatment and distillation of feed water with the total dissolved solids (TDS). Additionally, the potability of the water was assessed using the TDS level. The distillation process demonstrated a TDS removal efficiency of approximately 98%, reducing the TDS concentration from 9218 mg/L to 140 mg/L.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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Author Contributions

All the authors contributed to the conception and design of the study. Z.K. Khudair carried out the experimental work, collected and analyzed the data, and prepared the manuscript. A.F. Al-Hamdani supervised the research, provided scientific guidance, and reviewed the methodology and results. Emad Ali Disher contributed to the preparation, development, and characterization of the geopolymer–graphite ceramic material and reviewed the technical aspects of the study. Shilendra Kumar Shukla provided scientific consultation, reviewed the manuscript, and helped improve the interpretation of the results. All authors read and approved the final manuscript.

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Notation list

Symbol	Meaning	Unit
A	Basin (evaporation) area of the solar still	m²
E_{elec}	Electrical energy input supplied to the ceramic material	Wh
hfg	Latent heat of vaporization of water	kJ/kg (Eq. 3), J/kg (Eq. 4)
I	Solar irradiance intensity (average, on a horizontal surface)	A
m	Cumulative mass of distilled water produced over the exposure time t	kg
$\dot{m}$	Instantaneous distillate productivity rate	kg/s
P	Electrical power supplied to the ceramic material	W
t	Operating /exposure time	h (Eq. 1–3), s (Eq. 4)
T_a	Ambient air temperature	°C
T_g	Glass-cover temperature	°C
T_m	Ceramic material temperature	°C
T_w	Basin (brine) water temperature	°C
V	Voltage supplied to the ceramic material	V
η	Overall thermal efficiency (solar + electrical energy input basis)	%
η_i	Instantaneous thermal efficiency, also referred to as VTE in the figures	%
Abbreviations	**Meaning**	
AC	Alternating Current	
CR1	Ceramic sample/configuration 1 (23.5 × 4 × 3.5 cm)	
CR2	Ceramic sample/configuration 2 (24 × 24 × 3 cm)	
CSD	Conventional Solar Distillation (still) – the unmodified, baseline solar still	
DC	Direct Current	
PV	Photovoltaic	
SDWC	Solar still integrated with the geopolymer–graphite ceramic material (the modified system)	
TDS	Total Dissolved Solids	

VTE	Volumetric Thermal Efficiency – used interchangeably with the instantaneous thermal efficiency ηi (Eq. 4)
WHO	World Health Organization

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