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Charcoal and gravel basin lined solar still for brackish water purification

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Abstract

Solar still technology is one of the most cost-effective and efficient means of brackish water purification, particularly for tropical remote regions deprived of electricity supply. This study evaluates the impacts of lining the basin of a locally made solar still with energy storage materials at an equatorial location. During clear days, distillates were got from the distiller while its basin was lined with: (i) no material, (ii) black gravel, (iii) charcoal, and (iv) a mixture of both substances. Compared to when no basin liner was used, the volume of distillate obtained during active hours increased by approximately 9%, 26%, and 106%, respectively. However, during the night, the gravel-lined solar still had the highest output, and the peak hourly distillates ranged from approximately 9-24 ml, depending on the basin type. The daily thermal efficiencies for the four solar stills were 17.6%, 18.9%, 14.4%, and 20.4%, respectively. Turbidity, total dissolved solids, and total coliform counts in the offensive, cloudy brackish feed were reduced to the recommended limits for drinkable water. Besides the effect of solar radiation intensity on distillate production, the heat absorbance and transfer capabilities of basin liners are essential considerations for solar stills. A solar still, lined with a mixture of submerged black gravel and floating charcoal pieces, is recommended for brackish water purification due to outstanding distillate yield. Alternatively, an energy storage material that combines the qualities of both black gravel and charcoal should be developed for usage in solar still.

Keywords**:** *basin lining; brackish water treatment; energy storage materials; equatorial site; floating charcoal, solar distiller; submerged black gravel.*

1. Introduction

Apart from food and air, water is essential to human wellbeing and necessary for domestic uses such as cooking, washing, and bathing. Additionally, water bodies serve as a means of transport, electricity generation, and habitat for fishes, plants, and other organisms such as frogs and mayflies (Allan & Flecker, 1993; Poff et al., 1997). Living creatures require regular water intake for survival; mainly, the blood flowing throughout the human body to sustain life is mainly composed of water. Because an adult human body is composed of around 30% to 70% water, the body mass index depends on total water content (Brook, 1971; Chumlea, Guo, Zeller, Reo, &

Siervogel, 1999). Hence, to determine someone's health status, information on the water content, fat, and other bodily chemical components are needed (Gallagher, Visser, Sepulveda, & Pierson, 1996; Wells, & Fewtrell, 2006).

Insufficient body water content can lead to dehydration, seizure, brain swelling, spinal cord damage, high body temperature, dizziness, indigestion, diminished energy, low collagen, and skin blemishes. Although water cannot eliminate or substitute drugs, it can control ailments such as heartburn, cardiac failure, kidney failure, and high blood pressure (Rylander, & Arnaud, 2004; Sontrop et al., 2013; Higashihara et al., 2014). Food alone cannot satisfy the body's need for water, so enough fluid intake assists in the circulation of oxygen and nitrogen in the body. It also enhances metabolic activities such as waste removal through urinating and sweating. However, diarrheic diseases, typhoid, and death may arise from drinking unhygienic water (Hrudey, Payment, Huck, Gillham, & Hrudey, 2003; Fewtrell et al., 2005; Widerström et al., 2014).

Approximately 3% of the earth surface water is freshwater, while 97% is unsuitable for human consumption due to the high level of salts and other contaminants such as microorganisms and solid particles. Such contaminated water is regarded as brackish or salty when the level of dissolved salt is high. Over 80% of freshwater is frozen or buried in hard-to-access underground aquifers. Water pumps are used to extract underground aquifer water in some cases. Apart from natural occurrences, water contamination also arises from human activities such as waste disposal, industrialisation, and urbanisation (or climate change). Water deposits are not evenly distributed, and potable water must compete for them with agriculture and energy production reservations (Pimentel et al., 1997; Kalogirou, 2005).

Globally and particularly in Africa, the number of people without access to potable water is alarming, even as the human population continues to grow in the face of climate change (Falkenmark, 1990; Vörösmarty, Green, Salisbury, & Lammers, 2000). Nigeria is one of the African countries that do not have enough drinkable water for their large population. Water is abundant during the rainy season, but during the dry season, wells dry up, and stored supplies in tanks are also exhausted, leading to periodic scarcity of drinkable water. In addition, there are hygiene-related problems associated with supplies from the Water Board and other providers of table and sachet water (Ademiluyi, & Odugbesan, 2008; Aboyeji, 2013). Because water from water bodies like rivers and streams is mostly unhygienic, purification is necessary before consumption. Contaminated water can be purified through filtration, ozone, UV, and chlorination, but solar treatment is highly recommended (Yadav, & Sudhakar, 2015; Evangelista, Viccione, & Siani, 2019).

A solar still is a device that employs solar energy for water purification. It can be used without electricity, making it suitable for places where electricity supply is non-existent or intermittent. Solar water purification could not only eradicate several contaminants in one step, it is also simple, cost-effective, and non-disruptive. The technique involves evaporating water, then condensing the vapour, such that other substances such as heavy salts, minerals, and pollutants in the feed are not carried over to the output. Solar distillation has been used since the fourth century BCE, and industrial solar distillation plants were already in use as early as the 1800s. Desalination, the separation of salt and water in salty water, seems to be the earliest application of water distillation. Industrial processes have improved over the years, and in recent times, the focus on distillation has shifted from salt production to water purification (Kalogirou, 2005).

There are two types of desalination methods: thermal phase-change and membrane processes. While the former mimics the earth's natural water cycle by evaporating water using heat and condensing the vapour, the latter uses low electrical energy to reserve osmosis and electrodialysis. Although membrane processes are popular, the electrical energy needed for salt ionisation poses an obstacle to its deployment in some locations. Examples of thermal phase-change processes include multistage flash, multi-effect boiling, vapour compression, freezing, humidification or dehumidification, and solar still. Several solar still designs exist, such as single and multiple basin slope, pyramidal, wick, inverted, spherical, tabular, and miscellaneous solar stills (Kalogirou, 2005; Yadav, & Sudhakar, 2015; Kabeel, Arunkumar, Denkenberger, & Sathyamurthy, 2017; Nayi, & Modi, 2018).

Unlike other solar technologies (e.g., photovoltaics) and heat exchangers (e.g., running-water heaters), a solar still can obtain an efficiency of about 100% when it operates with stored solar energy. Specifically, solar distillation operates by passing solar radiation coming down from the sun through a transparent cover and heating the water in the basin to a temperature above that of the transmitting cover. As a result, the temperature and vapour pressure gradients within the solar still lead to vapour condensation underneath the cover. This condensate film trickles down through the collecting channels to a freshwater storing facility. A solar still consists of three essential parts and can be reemission of manufactured locally. The first is the glazing material, which transmits solar radiation to the base and prevents the radiation. This can be glass, plastic, or a dielectric material. The second part, which is the central unit of the solar still, is the absorber plate that absorbs the sun's radiant energy. This caters to the heat that turns water into vapour in the system. Insulators make up the third part, which can be rubber or wood. Altogether, they prevent the heat from escaping and host the non-active outlets for feed supply and removal. Such a simple technology, which drastically reduces the cost of water purification, could also include insulation and basin liners in the setup. Basin liners allows more energy to be stored in the solar still for quick attainment of peak temperature and higher production of distilled water (Banat, Jumah, & Garaibeh, 2002; Gugulothu, Somanchi, Devi, & Banoth, 2015; Yadav, & Sudhakar, 2015).

Apart from their size and the materials of the radiation transmitter and heat absorber, atmospheric factors such as solar radiation, air temperature, and wind speed also impact the productivity of solar stills. For instance, during the dry season, the volume of distillate can increase by as much as 18% compared to the rainy season (Egarievwe, Animalu, & Okeke, 1991). As a result, the volume of distilled water depends not only on the type of feed but also on the technology and the environment (Akash, Mohsen, Osta, & Elayan, 1998; Tiwari, Singh, & Tripathi, 2003; Oruc, Desai, Kenis, & Nuzzo, 2016; Narayanan, Yadav, & Khaled, 2020).

A conventional solar still has no additional components like the photovoltaic unit, pump unit, concentrators, etc., but could have basin liners. Besides the complexities and large space requirements, the additional units increase the cost of water purification. Ignoring the instances where phase change materials are deployed and large, complex and multi-unit solar water purification systems, the volume of distillate remains relatively insubstantial even when basin liners are used in conventional solar stills (Aybar, Egelioğlu, & Atikol, 2005; Gugulothu et al., 2015; Yadav, & Sudhakar, 2015). However, distillate production could be enhanced by about 20%–60% or more by increasing the temperature or energy of a solar still through adding one or more other units like solar thermal collectors (e.g., parabolic trough collector, evacuated tubes collector, flat plate collector), thermal chemical reaction unit, pumping unit, condenser, and power unit (Ayoub, & Malaeb, 2012; Kabeel et al. 2017; Narayanan et al., 2020; Panchal, Hishan, Rahim, & Sadasivuni, 2020).

Heat-absorbing substances, such as charcoal and black rubber mats, ink, and dye, can increase daily distillate production by 35% to 60%. Charcoal is outstanding because it uniquely reduces the thermal inertia of the system, such that when incorporated as a liner, the start-up time of the still is reduced. This is possible because charcoal mimics capillarity. It absorbs and re-radiates like a blackbody, reflecting incident radiation like a rough surface. Other heat-absorbing materials such as sand, stone, and gravel can also improve the efficiency of solar stills (Akinsete, & Duru, 1979; Naim, & Abd El Kawi, 2003; Alva, Liu, Huang, & Fang, 2017; Dubey & Mishra, 2021). Apart from the heat supplied directly by the sun, an absorbing agent also releases heat for the distillation process. Although theoretical designs produce significant outcomes, in practice, basin liners have marginal impact on performance, such that the distillate yield from conventional solar stills is rarely doubled (Murugavel, Sivakumar, Ahamed, Chockalingam, & Srithar, 2010; Gugulothu et al., 2015; Narayanan et al., 2020). The solution lies in using appropriate materials for all the components of the solar still, particularly the energy store. Besides the high absorptivity of black objects, gravels by nature or design are effective energy storage materials that gradually release absorbed energy over time and can be suitable for raising and sustaining the temperature of solar thermal technologies like the solar still. Gravels, when used for energy storage in a solar distiller, steadily transfer retained heat to the water for continuous evaporation to occur (Sakthivel, & Shanmugasundaram, 2008; Nafey, Abdelkader, Abdelmotalip, & Mabrouk, 2001; Elashmawy, 2021).

2. Objectives

This study evaluates the performance of a locally constructed solar still, whose basin is lined with floating charcoal and submersed black gravel, in purifying brackish water. The essence is to evaluate the improvement in the volume of distillate, if any, when the basin of our locally made solar still is lined with floating charcoal, submersed black gravel, and a combination of both the charcoal and gravel, compared to when no basin liner is used. Furthermore, apart from the performance evaluation of the experiments, the extent of impurities removal from the feed obtained from a slum community was ascertained for a typical distillate.

3. Materials and methods

3.1 Sites and analysis

To a large extent, the riverine and rural populace depend on water from rivers, which is not always suitable for drinking. Rainfall is rare, and water levels are low during the dry season. Consequently, such bodies are periodically full of contaminants. In this study, brackish water was collected from the Lagos Lagoon around Makoko, Lagos State, Nigeria (Figure 1). Although the surrounding regions can be considered an industrial hub, most of the Makoko areas have shanties built over water, where an estimated 200,000 people dwell and fish as their primary occupation. This place is regarded as the world's largest floating slum. Drinking water is delivered into the community through occasionally faulty long-distance pipes. While the state government is expected to develop the riverine communities in the future, an interim potable water source is necessary to sustain human lives (Ogunlesi, 2016).

Figure 1 Location where the feed water was collected at Makoko, Lagos, Nigeria.

Although the feed was collected from Makoko, the solar distillation was done at another site. Water samples were analysed using both standard classical and automated instrumental methods. While a digital Jenway 3505 meter (calibrated using standard solutions of pH 4.0 and pH 10.0) was used for measuring the pH, the total dissolved solids, conductivity, and turbidity were measured using a Hach conductivity meter. The physical/organoleptic, organic, and inorganic chemical constituents and the microbiological properties of both the feed and the output were determined. Furthermore, the microbial content in the water was measured in terms of heterotrophic plate counts (HPC), while the results were compared against the Nigerian Standard for Drinking Water Quality (NSDWQ). Besides, the impact of meteorological conditions at the experimental site (University of Lagos, Nigeria) on the performance of the constructed solar water still was evaluated.

3.2 Construction materials

As mentioned earlier, there are several solar water still designs. The one used in this study (Figure 2) was selected as it is the most economical and requires little maintenance (Tiwari et al., 2003). While the top of the solar still can be either glass or plastic, the former is preferable and was selected as the material. This is because a plastic solar still top produces low distillate yield and is degraded in the long term by the sun's ultraviolet rays (Ghoneyem, & Ileri, 1997; Cappelletti, 2002). A 4-mm thick window glass cover was installed, and black painted gravel and charcoal were used to line the aluminium basin; the frame of the still was a composite wall made up of 5-mm thermocole (inside) with a thermal conductivity of 0.02 W/mK and 18 mm of wood with a thermal conductivity of 0.6 W/mK (outside). Furthermore, a PVC (polyvinyl chloride) pump pipe designed for potable water system was used as a distillate channel as it is commonly available at a low cost. Silicon sealant was used to make firm contact between the glass cover and the frame. It also secured the cover to the frame and allows for differential thermal expansion and contraction between them (Yadav & Sudhakar, 2015). The insulating material in this study was wool fibre with a thermal conductivity of 0.048 W/mK and a thickness of 10 mm.

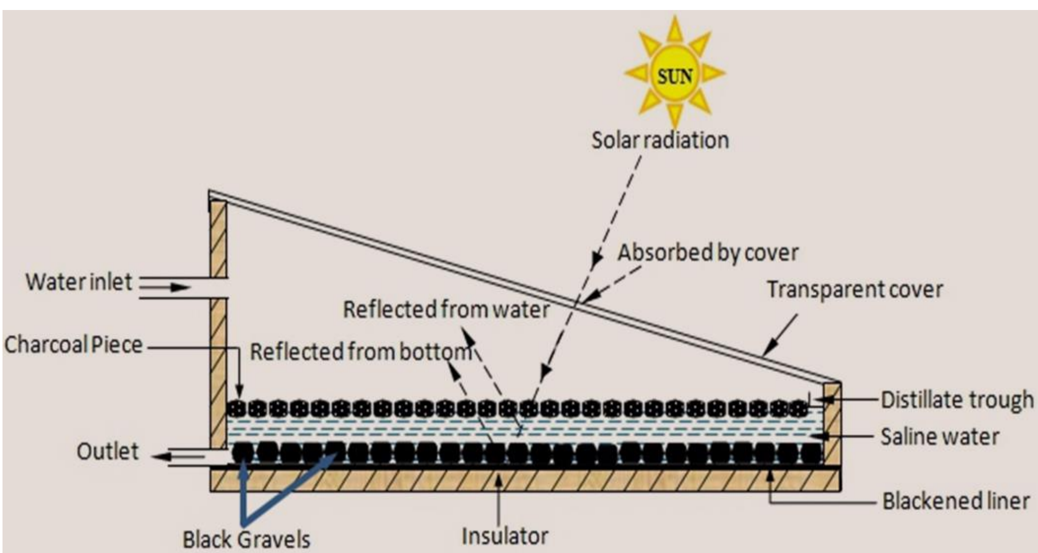

Figure 2 Schematic sketch of a solar still lined with black gravel and charcoal pieces.

3.3 Experimental setup

The experiment was performed in the water tank field of the Faculty of Science building, University of Lagos, under actual environmental conditions. The still was positioned facing south to ensure long hours of direct incident solar radiation. The single-slope solar still had a basin area of 0.21 m^2 (0.50 m by 0.42 m in dimension), and the transmitting glass was inclined to the latitude (6.5°) of the location while the tallest and shortest walls of the still were 0.24 m and 0.18 m tall respectively (Figure 3). Typically, the feed should be supplied into the solar still continuously but during nocturnal production, the system should be fed once. The supply system used includes an overhead bucket, hosepipes to transport water into the still, and regulator valves. The feed was introduced before 8:00.

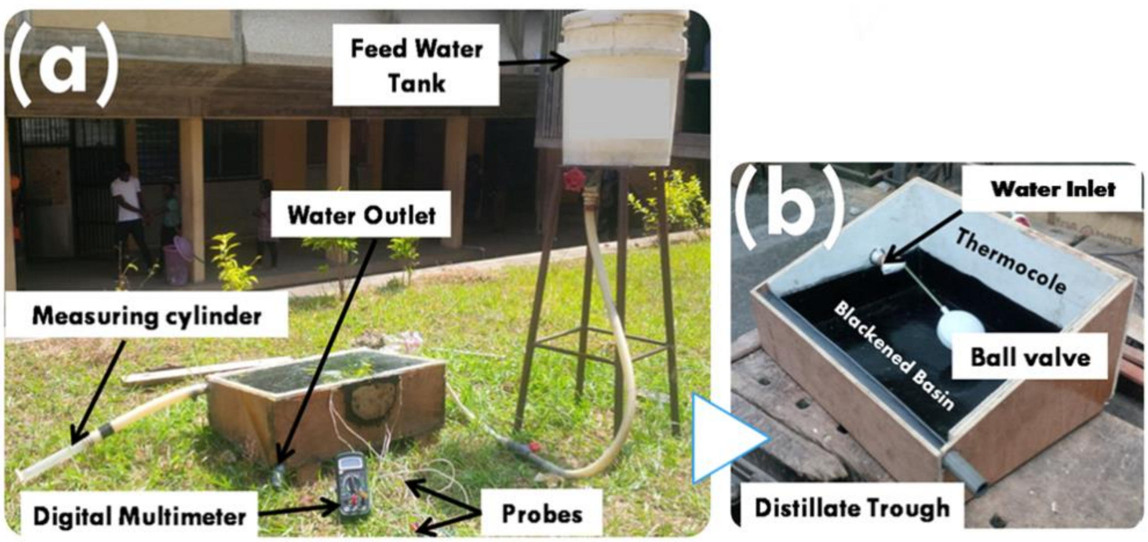

Figure 3 Photographic diagram of the solar still; (a) The full set-up (b) The fabrication showing the ball valve and the distillate trough.

There are three main components of a typical solar still, namely the insulated sides, the absorptive basin, and the cover. The sides and bottom of the container (basin) were insulated with wool fibre to reduce heat loss from the feed solution through these parts. They were also painted black to maximise light absorption, while the distillate trough was sloped towards the discharge end to aid with the freshwater flow.

An inlet port and an outlet port were provided at the top of the sidewall and the bottom of the basin tray for feeding brackish water into the basin and draining water from the still for cleaning. A hole in the back wall of the basin also allowed the absorbing materials to be loaded into the basin and provided access to the inside of the still for the temperature probe. When the still was in operation, the hole was closed with a cover and silicon rubber sealant to avoid heat and vapour loss. A ball valve was attached to the inlet to regulate the flow rate of the feed water and keep the level within the still constant. Incident thermal radiation would raise the interior temperature, increasing the vapour pressure of water inside the still. When the hot water vapour travels upward and condenses on the relatively cool cover, it trickles down the inclined plane with help from gravity, to be collected into a distillate trough. The trough was shielded from direct radiation to avoid re-evaporation.

Sensor probes were attached to strategic spots on the still and housed within the still for measurements of hourly temperature of the brackish water, vapour, inner and outer covers, and basin. Furthermore, to ensure that the temperature of the glass was measured correctly and not affected by the ambient insulating environment, a tape was applied to cover the sensor. A calibrated mercury thermometer accurate to 2℃ was used to record the ambient temperature. Hourly distillate output was measured with a calibrated cylinder fitted at the discharged end of the distillate trough.

The hourly solar radiation intensity was measured using a calibrated Middleton pyranometer, which gauges the total solar radiation received by a region per unit area. The still was lined with pieces of charcoal and black gravel at different times. It was then immediately sealed, and hourly readings of distillate output and temperature were recorded. Before starting the test, the unit was filled with 8 cm of water from the bucket fitted on a stand nearby. The glass cover was also cleaned for dust and dirt particles before and during the experiment. The tests started at 8:00 and continued till 20:00 local time, from January to February 2014. Measurements of incident solar radiation, ambient temperature, humid air temperature, cover temperature, brackish water temperature, and distillate yields were monitored and recorded hourly. Though other regular readings were not taken after 20:00, the volume of distillate during the night was read off the cylinder the following morning before resetting the experiment.

3.4 System thermal efficiency

Radiant energy from the sun passing through the glass cover was absorbed by the water mass and basin liner or/and metallic absorber at the bottom of the solar still. As the absorbed energy increased, vapour formed at the surface of the water rose and condensed on the bottom surface of the transparent cover. The mathematical analysis of the solar still considers the glass cover, water mass, and basin liner. The energy balance of solar still states that the total absorbed solar energy equals the energy transmitted through the glass cover, losses from the bottom and edge of the construction and the energy absorbed by the system. It is assumed that the system is in a quasi-steady state, no vapour leaks from the still, no energy absorption by the glass cover, and the heat capacities of the glass cover, absorbing material, and insulating material are neglected. Furthermore, the principle of operation also assumes that the temperature of the glass cover is homogenous at every point both at its top and bottom side, condensation at the glass cover is a film type, and the surface areas of the glass cover, water surface, and base of the solar still are equal. Two central heat mechanisms govern the fundamental analysis of the system, namely the internal heat transfer comprising radiative, conductive, and evaporative, and the internal heat transfer (Sampathkumar, Arjunan, Pitchandi, & Senthilkumar, 2010; Yadav, & Sudhakar, 2015; Layek, 2018).

With regards to the internal energy transfer, the energy balance equation for the transparent glass cover, which mainly accounts for the energy of the system, can be given as:

$$Q_{GA} = r_1 H_S + Q_{CW} + Q_{EW} + Q_{RW} \qquad 1,$$

Q_{GA} is the rate of heat transfer from glass cover to ambient (W/m^2), r_1 is the solar energy absorbed by glass cover (W/m^2), H_S is the solar radiation absorption coefficient for the glass cover, while Q_{CW} is the rate of convective heat transfer from water surface to underneath the glass cover (W/m^2), which can be simplified as:

$$Q_{CW} = h_{cw}\left(T_w - T_{gi}\right) \qquad 2,$$

h_{cw} is the convective heat transfer loss coefficient (W/m^2/℃), T_w is the water temperature, and T_{gi} is the temperature underneath the glass cover.

Q_{EW} is the rate of evaporative heat transfer from the water surface to underneath the glass cover (W/m^2), given as:

$$Q_{EW} = h_{ew}\left(T_w - T_{gi}\right) \qquad 3,$$

h_{ew} is the evaporative heat transfer loss coefficient (W/(m^2 ℃)).

Furthermore, Q_{RW}, the rate of radiative heat transfer from the water surface to underneath the glass cover (W/m^2), is given as:

$$Q_{EW} = h_{rw}\left(T_w - T_{gi}\right) \qquad 4,$$

h_{rw} is the radiative heat transfer coefficient (W/(m^2 ℃)).

The energy balance equation for water mass is given as:

$$\tau_2 H_S = (C_w m_w)\frac{dT_w}{dt} + h_T(T_w - T_{gi}) + h_3(T_b - T_w) \quad 5,$$

τ_2 is the solar flux absorbed by the water mass, $(C_w m_w)\frac{dT_w}{dt}$ represents the energy absorbed by water mass by virtue of its temperature T_w, h_T is the energy transmittance coefficient (W/(m^2 °C)), h_3 is the heat transfer coefficient of the solar still insulator, and T_b is the basin temperature.
At the bottom of the still, the energy balance equation for the basin liner is:

$$\tau_3 H_S = h_3(T_b - T_w) + h_b(T_b - T_a) \quad 6,$$

τ_3 is the solar flux absorbed by basin liner, $(C_w m_w)\frac{dT_w}{dt}$ represents the energy absorbed by water mass by virtue of its temperature T_w, h_T is the energy transmittance coefficient (W/(m^2 °C)), and T_b is the basin temperature.

On the other hand, the external heat transfer, which arises from the heat exchange between the outside, i.e., top, sides and bottom, of the still and its surroundings, can also be expressed in terms of radiative, convective, and conductive components. It involves the total upper heat loss or heat lost by the glass cover and the heat transfer of the insulating material of the solar still to the environment. The total upper heat loss is the sum of both radiative and conductive heat losses. The rate of radiative energy transfer from the glass to the atmosphere can be given as:

$$Q_{rgo} = h_{1go}(T_{go} - T_{sky}) \quad 7,$$

h_{1go} is the radiative heat transfer coefficient from glass to sky (W/(m^2 °C)), T_{go} is the temperature of top of glass cover, T_{sky} is the sky temperature. h_{1go} depends on air temperature and glass temperature.
The rate of convective energy transfer from the glass to the atmosphere can be expressed as:

$$Q_{cgo} = h_{2go}(T_{go} - T_a) \quad 8,$$

h_{1go} is the convective heat transfer coefficient from glass to sky and is dependent on wind velocity.
Although the still losses heat through its top, bottom and sides, the basin also sends back heat to the water mass. The rate of conductive heat transfer from basin to water mass is:

$$Q_b = h_b(T_b - T_w) \quad 9,$$

h_b is the conductive heat transfer coefficient of the basin.
To calculate the amount of distillate produced by the solar still, besides determining the overall external heat loss coefficient, the above expressions are further solved algebraically under some conditions (Sampothkumar et al., 2011; Yadav & Sudhakar, 2015). The hourly distillate from the solar still is given as:

$$m_{we} = \frac{h_{ew}(T_w - T_{gi})}{L} \quad 10,$$

m_{we} is the mass of hourly distillate of the solar still, and L is the latent heat of vaporisation of water.
The thermal efficiency of the still can be defined as the ratio of thermal energy utilised for the distillate yield to the incident solar energy over a given time interval. Ignoring the individual thermal contribution of the different basin liners, the thermal efficiency of the respective solar still adopted in this study can be expressed as:

$$\eta_i = \frac{m_{we} \times L}{A_c \times G_T} \quad 11,$$

A_c is the area of the still (m^2) while G_T is the incident solar radiation (W/m^2).

4. Results

4.1 Atmospheric and system factors

The experiments were performed from January to February 2014. To ensure a consistent assessment, only the results from cloudless days were retained because the solar still system was tested in four different configurations. As previously mentioned, the four test configurations were, when no basin liner was used, when floating charcoal was used as a basin liner, when black charcoal was used as a liner and when both the charcoal and gravel were used as energy storage materials in the solar still. Solar irradiation intensity varied through the day, such that the intensity gradually increases in the morning, reaches a maximum at 14:00, and steadily declines in the evening hours. Between 9:00 and 18:00, the typical hourly aggregate intensity of solar radiation was about 4.39 kW/m^2, with a maximum insolation of 800.4 W/m^2 and a minimum hourly value of approximately 96.15 W/m^2. The hourly ambient temperature ranged from 26.5°C to 40°C, peaking at around 16:00, while the daily average ranged from 28.8°C to 33.5°C.

Figure 4 shows the change in relative humidity with regards to solar radiation for a selected period during the experiment. Characteristically, while relative humidity started high at 8:00, solar radiation was low. As the day proceeded, humidity decreased sharply, while radiation increased. At 10:00, humidity reached its lowest point in the day and began increasing again, a trend that would continue for the rest of the day. Solar radiation increased until it reached its peak at 14:00, after which it gradually diminished to a minimum by 20:00. The prevailing relative humidity was at a minimum value of 34% at 10:00, while the maximum was found to be 80% at 20:00. Hence, the highest relative humidity values coincided with zero radiation (Figure 4).

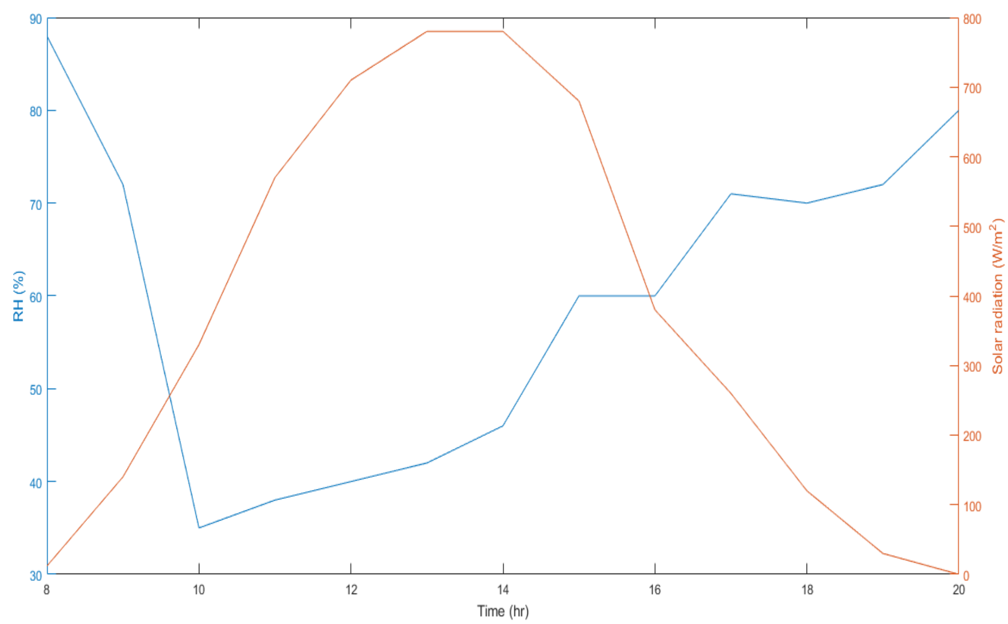

Figure 4 Hourly variations of relative humidity and solar intensity between 8:00 and 20:00.

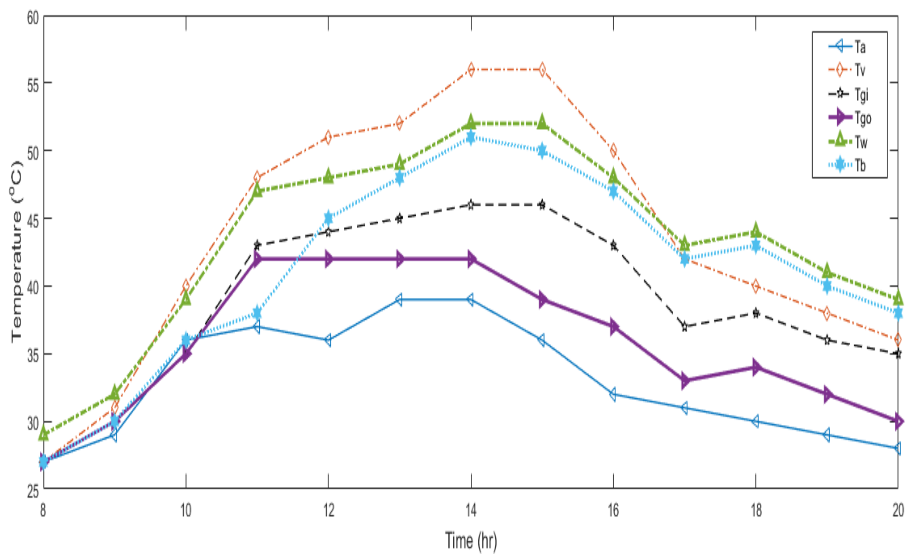

Figure 5 Typical hourly variation of ambient and system temperatures, where *Ta* is ambient, *Tv* is vapour temperature, *Tgi* is inside glass temperature, *Tgo* is the outside glass temperature, *Tw* is the water temperature, and *Tb* is the box temperature.

In the bright hours of the day (8:00-16:00), the vapour temperature of the still was at its peak because of the large amount of absorbed solar radiation – and the water molecules had enough energy to evaporate at the maximum temperature (Figure 5). From 17:00 onwards, the inversion between water and vapour temperatures indicated that the heat accumulated by the basin during the sunlight hours has been transferred to the water, raising the water temperature to its highest during this period. At 18:00 precisely, the vapour temperature (*Tv*), along with the ambient temperature (*Ta*, which still remained the lowest at around this regions) both continuously decreased after 17:00, whereas the temperatures of the water, the top and bottom of the glass, and the box increased instead. As long as the glass temperatures remained much lower than the vapour temperature within the solar distiller, condensation would occur. The maximum temperatures were always recorded between 15:00 and 16:00. They ranged from 29–53℃ for the water mass, 29–56℃ for the vapour, 28–47℃ for the inner cover, 28–42℃ for the outer cover, and 27– 51℃ for the basin. The ambient temperature was in the range of 28℃ to 39℃.

Usually, when the solar radiation intensity was high, the atmospheric humidity was rather low (Figure 4). A comparison of the typical trend of solar radiation from Figure 4 with the temperature patterns in Figure 5 reveals that both atmospheric and system temperatures varied directly proportionally to the solar radiation intensity. Altogether, when both the ambient temperature and the solar radiation were high, the relative humidity was low. When the comparison was extended to Figure 6, the effect of ambient climate conditions on the solar still performance was apparent. Distillation productivity was maximised when relative humidity was low, solar radiation was high, and temperature was high. However, it should be noted that the distillate volume also depended on the basin liner type, which also affected the temperatures within the still.

4.2 Still performance

Although the results are not presented in this report, it was observed that an unexpected decline in the intensity of solar radiation due to a passing cloud caused a dip in the amount of distillate collected compared to the expected output for a completely clear sky. Volumetric production rates for the four basins of the solar still are displayed in Figure 6 for the mode of operation in a sample (clear) day. The four basins were the conventional solar still where no liner was used (CSS), the basin lined with black-painted gravel (GLSS), the charcoal-lined basin

(CLSS), and the dual charcoal and black-painted gravel basin liner solar still (GCLSS). During the night and early morning period from 20:00 to 7:00, the largest volume of distillate was obtained from the GLSS, followed by the GCLSS, CSS, and CLSS, respectively (Figure 7). However, the volume of distillate collected during this time is minimal compared to the volume collected between 8:00 and 20:00 (Figures 6 & 7). As expected, significant volumes of distillates were obtained only between 12:00 and 15:00, when solar radiation was the most intense. A basin liner can boost distillate production by over 100% during this period. For instance, the maximum obtained distillate was approximately 7 ml for CSS at 14:00, 10 ml for GLSS at 15:00, 12 ml for CLSS at 13:00, and 24 ml for GCLSS at 14:00. The maximum hourly distillate of GCLSS was slightly more than 300% that of CSS (Figure 6).

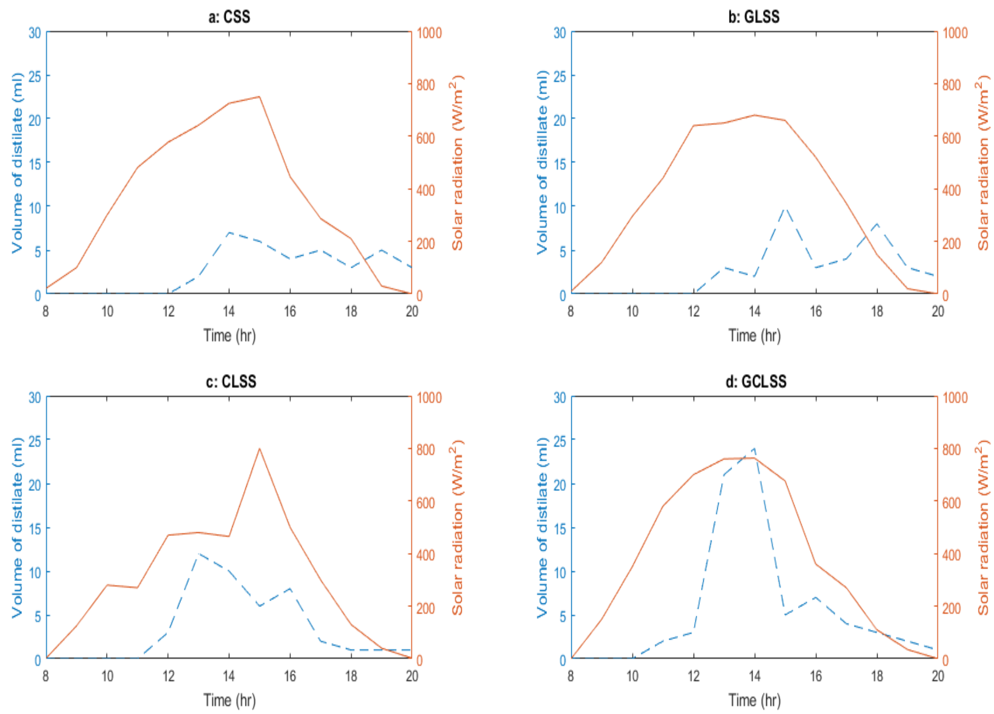

Figure 6 Hourly distillate yield and solar intensity for the four different solar still basin liners. The dashed blue lines represent the volume of distillates The thick continuous red lines represent the solar radiation. Figure 6a is the conventional solar till (CSS), 6b is the black gravel lined basin (GLSS), 6c is the charcoal lined basin, and 6d is the basin lined with both the gravel and charcoal.

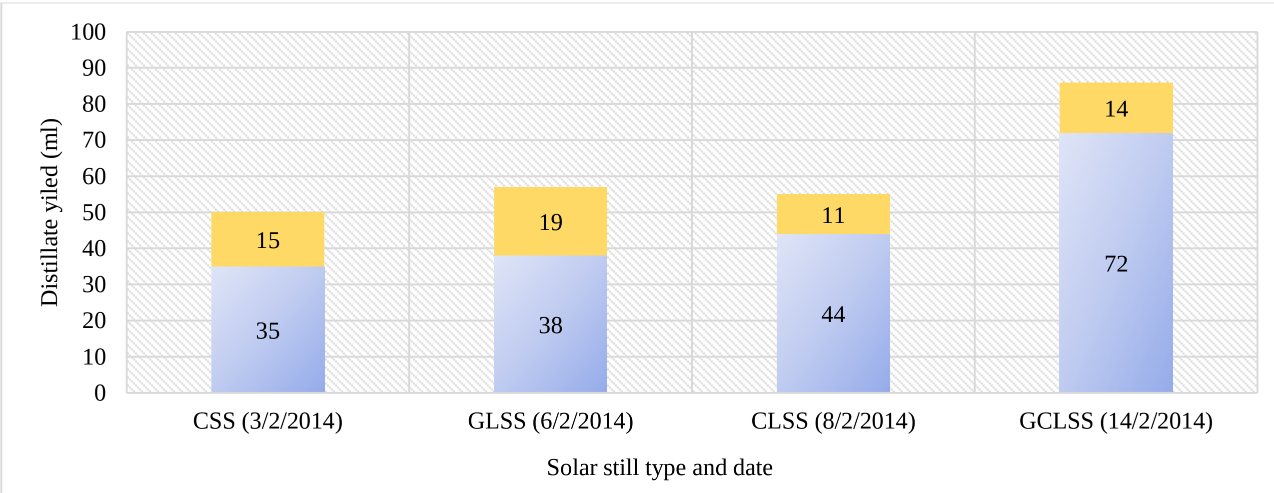

Figure 7 The volume of distillate from the different solar stills; where the top region of the bar chart indicates the night production while the bottom part indicates the daytime distillate.

The solar still absorbs energy for a few hours before distillation occurs. During the experiments, the CSS and GLSS started producing distillate by noon, the CLSS started an hour earlier by 11:00, while the 'dual control' liner started to distil two hours earlier by 10:00. This indicates that a combination of black gravel and charcoal pieces can absorb solar radiation faster. Hourly aggregates of solar radiation were 4.5, 4.5, 3.8 and 4.7 (kW/m^2) for the CSS, GLSS, CLSS, and GCLSS, respectively. Although the basin lined with charcoal received the lowest solar energy, it still had a better yield than conventional, and the black-painted gravel basin lined stills during the daytime.

Between 8:00 and 20:00, the GCLSS produced the most outstanding amount of distillate compared to the solar still without any basin liner. Distillate production improvements of approximately 106%, 26% and 9% were attained by GCLSS, CLSS and GLSS, respectively. In total, however, the respective total distillates were 50 ml (CSS), 57 ml (GLSS), 55 ml (CLSS), and 86 ml (GCLSS), which implies that marginal improvements of 14%, 10%, and 72% were achieved using the three basin liners. Not much distillate was produced at night, as the still was cleaned, and the basin liners changed early in the morning at 7:00. The ratio of daytime to overnight distillate production was around 4:1.

The conditions of the four solar stills in Figure 7 were also used for calculating efficiency. The average thermal efficiency of the conventional solar still was 17.6%, ranging between 2.07% and 97.6%. The thermal efficiency of the black gravel-lined still was 18.9%, ranging between 1.3% and 97.5%. The thermal efficiency of the charcoal-lined solar still was 14.4%, ranging between 1.4% and 99.2%. The thermal efficiency of the dual lined basin, i.e., GCLSS, was 20.4%, ranging between 3.3% and 99.9%. Generally, each unit had the lowest efficiency right after sunrise, while the absorbed energy gave them the highest efficiency right after sunset.

Solar stills productivity depends on numerous factors like solar radiation intensity, and ambience temperature, wind speed, and dust. Notably, the quantity and depth of basin liners can adversely impact distillate production under certain conditions (Bataineh & Abbas, 2020). Because the efficiency formulation considers mainly distillate output and solar intensity while somewhat neglecting other factors, the efficiency does not necessarily correspond with the distillate volume produced by the still. Although the conventional solar still efficiency was higher than that of the charcoal-lined still, the reserve was the productivity case. It could be due to the depth and quantity of charcoal in the water mass, which was not investigated. Nonetheless, the performance of the solar still lined with a combination of floating charcoal and black gravel was outstanding in terms of both productivity and thermal efficiency.

4.3 Water quality

Table 1 shows the measured values along with the recommended standards for water quality. There are some values where both the feed and the distillate were already within the acceptable level. For instance, the distillate acidity or pH was within the range of 6.8 to 8.5, as recommended by NSDWQ, while the conductivity of the water decreased from 867 mS/cm to 81 mS/cm, both below the permissible limit of 1000 mS/cm.

Table 1 Physio-chemical properties of a typical feed water and distillate in comparison with the Nigerian Standard for Drinkable Water Quality (NSDWQ).

S/no	Physical, chemical, and microbiological quantities	Feed water	Distilled water	NSDWQ (Maximum permitted level)
1	Chemical oxygen demand (mg/l)	74	26	-
2	Colour	Cloudy/light brown	Clear/colourless	Clear/colourless
3	Odour	Irritating odour	Unobjectionable	Unobjectionable
4	pH	7.52	7.46	6.8-8.5
5	Turbidity (NTU)	31	4	5
6	Conductivity (μS/cm)	867	81	1000
7	Total suspended solids (mg/l)	60	30	-
8	Total dissolved solids (mg/l)	640	60	500
9	Total coliform counts (cfu/ml)	58	0	10
10	Total bacterial counts	1.10×10^3	2.0×10^2	-

Turbidity depends on the quantity of suspended solid matter. It measures the light-emitting properties of water, which indicates the quality of waste discharge in terms of its colloidal matter content. The feed water had a turbidity of 31 NTU, while the distilled water had a turbidity of 4 NTU, indicating that the solar still could reduce this parameter to below the NSDWQ recommended value of 5 NTU. Water turbidity is directly related to the risk of gastrointestinal diseases in humans (Tinker et al., 2010).

Total dissolved solids (TDS) for the feed water stood at 640 mg/L, while that of the distillate was 60 mg/L (Table 1). From these results, the solar still produced water with TDS lower than the recommended value of 500 mg/L. The still also reduced the total suspended solids of the feed water from 60 mg/L to 30 mg/L in the distillate. According to the results, the water was disinfected with a removal efficiency of 100% and 98.2% for total coliform counts and total bacteria counts, respectively. The former decreased from 58 CFU/ml to 0 CFU/ml, while the latter declined from 1×10^3 CFU/ml to 2×10^2 CFU/ml.

5. Discussion

Researchers have compared between different heat absorbers in solar stills (Kabeel et al., 2017; Layek, 2018; Dubey & Mishra, 2021). Okeke, Egarievwe, and Animalu (1990) used both coal and charcoal as basin liners in a study conducted in Nsukka, Nigeria. The size of the solar still used in this study was relatively small, and charcoal and black gravel were selected as basin liners due to their thermal properties. A typical charcoal piece, whose black colour enhances the absorption of incident radiation, is porous and exhibits capillary action by maintaining a wet surface when floating on water. It increases the surface area of the basin's evaporative liner, resulting in a greater distillate output. Meanwhile, submerged gravel, which does not display any capillary action, is less absorbent of incident radiation than charcoal. It is an excellent thermal absorber and energy storage medium; therefore, it enhances convective heat transfer from its surface to the surrounding water when heated. This would keep the water temperature constant, enhancing continuous evaporation and extending distillation way into the night. Like the standard method of boiling water, where heat is applied to the bottom of the container, the hot gravel heated the bottom of the still, aiding evaporation at the surface of the feed. The use of gravel, besides storing energy, also prevents heat loss from the bottom of the still.

Unfortunately, a mere 9% increase was obtained with a gravel liner in this study, when this figure could be as high as 17% to 23% (Nafey et al., 2001; Kabeel et al., 2017; Elashmawy, 2021). Contrary to the 35% to 60% improvement for charcoal mentioned earlier, only a 26% improvement was achieved in this study, possibly due to high atmospheric variations or its depth in the water mass. Irrespective of the small size of the solar still used, the present study benefits uniquely from adopting both charcoal and black painted gravel as basin liners. Distillate yield experienced a rare increase of 106% during certain hours compared to when no basin liner is used. In this case, the charcoal floats with submerged gravel in the feed.

Solar stills should be economical and efficient when used to produce drinkable water, particularly if deployed in remote areas with no electricity. Sand and other substances can be incorporated into the solar still for energy storage. However, modifications often trade yield and efficiency for complexity (Yadav & Sudhakar, 2015), though such is not the case in this study because cheap and readily available heat exchangers were deployed in the conventional solar still. Due to changes in the size of solar stills and meteorological factors, it is not easy to make adequate comparisons across studies. Nonetheless, this study reveals that the deployment of local and appropriate energy storage materials in a solar still can remarkably improve the system's performance.

The bottom of a solar still is made of a metal like aluminium that can rapidly absorb solar radiation, but also quickly shed heat under unfavourable weather conditions. Since changing weather can impact the performance of a solar still, the inclusion of heat storage materials aids in stabilising the system. Properties such as availability, flammability, corrosiveness, toxicity, heat capacity, heat conductivity, chemical stability, cost, etc., are often central to the choice of material for energy storage. Carbon-based nanocomposites outperform other materials like metals and metal-oxides in thermal energy storage (Herrmann & Kearney, 2002; Alva et al., 2017; Badenhorst, 2019; He et al., 2021). Both the charcoal and black gravel used as basin liners in this study can be linked to carbon. Charcoal is a pure black variant of carbon without hydrogen and oxygen, while gravel is composed of many substances, including carbonates (Wu, Wang, & Meng, 2017).

Additionally, carbonates have very high melting temperatures and low transfer capabilities, making them the best energy storage materials (Ge et al., 2014; Badenhorst, 2019; He et al., 2021). Several other carbon compounds are associated with energy, e.g., carbon dioxide and methane, which absorb and retain atmospheric heat and cause global warming. Propane and butane are commonly used as cooking gas, while coal is used to fuel vehicles and power generation. Furthermore, charcoal and coal can be used for cooking, and their combustion produces a lot of energy while releasing greenhouse gases into the atmosphere (Robertson, Paul, & Harwood, 2000; Foell, Pachauri, Spreng, & Zerriffi, 2011). Graphite and graphene are carbon materials with many applications, including as chemical energy materials for batteries, capacitors, and superconductors (Pumera, 2011; He et al., 2021). Since carbon-based materials are frequently associated with energy, the development of a new material that combines the properties of charcoal and gravel is recommended for thermal energy storage in solar stills. Moreover, because the inclusion of evaporation enhancers at the top and bottom of the solar still increases the volume of distillate, further studies should also consider designing an evaporation device for the middle section of the still. In addition to acquiring a quality photothermal material for efficient energy conversion, factors like appropriate still design, fast evaporation enablement, and optimisation of absorbed heat energy should be considered for the improvement of solar still technology (Nayi & Modi, 2018; Chen, Kuang, & Hu, 2019; He et al., 2021).

6. Conclusion

Solar stills are simple, efficient and cost-effective technologies for overcoming freshwater shortage, particularly in the remote areas of developing countries, such as Lagos, Nigeria, where there is sufficient solar radiation. Their performance can easily be improved with non-conventional techniques and designs. This study presented experimental results for a single-slope, flat-basin solar distiller, with various absorbing materials such as submerged black gravel and floating charcoal as liners, in which brackish water from the world's largest water slum was purified. The still was tested under four different basin-lined conditions: CSS, GLSS, CLSS and GCLSS, on clear days so as to eliminate a variable. From early morning to evening (8:00–20:00), productivity was highest in the GCLSS design, with a recorded distillate yield of 72 ml. In total, the percentage increase in the volume of distillates of the other basin liners over CSS under clear skies were 9%, 26%, and 106%, respectively. Hence, GCLSS is recommended for purifying brackish water due to its unique performance. Thermal efficiency is not always directly proportional to productivity due to the numerous factors that impact a solar still's performance. The highest still temperatures and the highest distillate production rate occurred between 13:00 and 15:00. In contrast to the feed, the output was free of solids, and its conductivity, TDS, and total suspended solids decreased by 68.8%, 90.6%, and 50%, respectively. Turbidity was reduced from 31 NTU to 4 NTU – a removal efficiency of 87% – while the electrical conductivity of the distillate is 89.7% lower than that of the feed water (867 mS/cm and 81 mS/cm, respectively). Hence, as expected, an excellent level of microbial removal was attained in this experiment. A limitation of this study was that the different basin liners were not tested simultaneously. However, since the weather condition during testing was kept as a control, in that all tests were performed under clear skies settings, there is a marginal possibility that weather may have affected the results. Further studies should be considered in improving the quality of the energy storage material for a solar still.

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