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RESEARCH ARTICLE

Investigating the performance of periwinkle shell (tympanotonos fuscatus) as energy storage material in a passive solar still

G.U. Akubue[1,2], C.E. Nnaji[1,3,4], F. I. Abam[5,6,*], C. Mbohwa[6]

[1]National Centre for Energy Research and Development, University of Nigeria, Nsukka, 410001, Nigeria
[2]Mechanical Engineering Department, University of Nigeria, 410001, Nsukka, Nigeria
[3]Africa Centre of Excellence for Sustainable Power and Energy Development, (ACE–SPED), University of Nigeria, Nsukka, 410001, Nigeria
[4]Economic Department, University of Nigeria, 410001, Nsukka, 410001, Nigeria
[5]Department of Mechanical Engineering, University of Calabar, Calabar, 540001, Nigeria
[6]College of Science, Engineering and Technology(CSET), Sustainability Engineering and Future Technologies (SEFT) Flagship, University of South Africa, Pretoria, 0002, South Africa

Abstract

Solar desalination remains a viable technique for addressing the lack of clean water in off-grid and arid locations. Low productivity and over-dependence on the available solar radiation are the main drawbacks of the technology. In this study, the effects of integrating periwinkle shell, an abundant marine bio-waste, as a sensible heat storage material and porous absorber, on the performance of a single-slope passive solar still were experimentally investigated at Nsukka, Nigeria (lat. 6.87°N and long. 7.38°E). Two solar stills, a conventional solar still and a periwinkle shell-assisted solar still, were fabricated with identical technical specifications and experimentally evaluated using equal water masses, with the primary objective of enhancing the productivity of the conventional solar still. The shells were sourced, cleaned, painted black, and evenly spaced in the periwinkle shell-assisted solar basin to improve thermal energy retention and yield. On an hourly basis, the distillate yields and temperatures of the major components were recorded to assess their performance. The results showed a 13.38% increase in daily freshwater yield. The energy and exergy efficiencies of the periwinkle shell-assisted solar still and the conventional solar still were 48.92% and 2.25%, and 41.77% and 1.53%, respectively. These improvements were attributed to the thermophysical properties of the periwinkle shell, thereby demonstrating the potential of marine bio-waste as a robust, sustainable, cost-effective alternative to sensible heat storage materials for low-temperature thermal systems such as solar stills and crop dryers. The findings underscore the viability of the shell in supporting the waste-to-energy nexus, offering economic benefits with minimal environmental impact.

Keywords: Solar still, periwinkle shells, energy storage material, productivity enhancement, exergy

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1. Introduction

Freshwater availability is currently one of the significant problems the world is facing today, especially in the remote, off-grid, and arid locations [1]. With rapid urbanization, industrialization, and increasing human and animal populations, the available freshwater is currently stressed. According to Abdelaziz et al. [2], about 25% of the world's population will experience freshwater scarcity this year, with about 66.67% of the said population facing acute water stress, leading to serious health issues. Nevertheless, freshwater can be produced through various methods, such as reverse osmosis, multistage flash, multi-effect distillation, and electrodialysis. These techniques, however, are energy-intensive and depend entirely on fossil fuels which are not only finite but are also currently contributing to serious environmental threats, such as global warming. Therefore, alternative freshwater production techniques to conventional methods are being sought; one such

*Corresponding Author
E-mail Adress: fidelisabam@unical.edu.ng

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technique is solar desalination. Solar desalination uses the freely available solar energy to produce freshwater with a solar thermal device called solar still. A solar still consists of an insulated basin into which saline, contaminated, or brackish water is introduced to produce freshwater. The top of the basin is sealed with a glass cover to allow penetration of solar energy and condensation of water. The major components of solar still are the basin, the insulator, and the glass cover [3]. Unlike the conventional methods, this device is cheap, can easily be fabricated and maintained, and is not entirely dependent on fossil fuels, thus remaining the best alternative technique for freshwater production mostly in isolated and arid locations with less population, and lacking expensive grid-connected electricity [4]. Therefore, a solar still is a sustainable, renewable-energy-based approach for water purification that reduces both energy consumption and environmental emissions. It, however, faces some challenges such as low freshwater production and low thermal efficiency owing to the device's over-dependence on available solar radiation and inadequate heat retention during periods without sunlight.

2. Literature review

Two basic improvement mechanisms have been identified to overcome the above challenges: the passive and the active mechanisms [5]. Passive techniques depend on modifications to shape and material, whereas active methods rely on external mechanical or electrical components, such as solar collectors and heaters, in addition to the freely available heat from the Sun. Jani and Modi [6] and Alwan et al. [7] conducted a review of studies on techniques to enhance the distillate yield of solar desalination systems. Recently, the use of energy storage materials as passive mechanisms, especially sensible heat storage materials (SHSM), to improve the distillate yield of solar stills is gaining attention. Sensible heat storage materials can absorb excess solar heat during peak sunlight hours and release it to the immediate environment, such as a water basin in a solar still, during periods of low solar intensity, thereby enhancing productivity. By absorbing excess heat, the SHSM reduces heat loss from the solar still, thereby increasing the overall energy input. Above all, SHSM are cost-effective and freely available compared to other heat storage materials such as latent heat storage materials (LHSM).

Extensive experimental work on sensible-heat storage materials to enhance the productivity of solar stills has been conducted. For instance, Karthick et al. [8] used an Omani Rockstone bed as a sensible heat storage material to enhance the distillate yield of a single-slope solar still. The modified still increased overall productivity by 18.6% compared with a similar conventional solar still. Rajamanickam et al. [9] also investigated the effect of charcoal-filled cylinders and orientations in a solar still. They compared two orientations of charcoal-filled cylinders' and a conventional type. Findings showed that while the productivity of both orientations were enhanced compared to a traditional type, the specific enhancements were 43.33% for the vertical type and 20% for the horizontal type. Again, comparing the effect of sand and jute-wick on the productivity of solar still, two modified solar stills were investigated by Kabeel et al. [10]. These are a solar still with sand as sensible heat storage, and a solar still with both sand and a jute wick. The investigative results indicated that both modified solar stills had higher distillates than the conventional type. However, the modified solar still with both sand and jute wick produced 2.85 kg/m2, solar still with only sand produced 2.75 kg/m2, and the conventional solar still produced 1.2 kg/m2. Again, using oil palm shells as sensible heat storage material, Sibagariang et al. [11] examined the temperature characteristics of solar still components, freshwater productivity, energy and exergy analysis, and economic analysis of a double slope single basin passive solar still in Indonesia using three different masses of the oil palm shells; 5, 3, and 1 kg, and a conventional solar still. The experimental studies indicated that the productivity of oil-palm-shell-integrated solar stills exceeded that of the conventional type by 10–39%.

By comparison, the energy and exergy efficiencies were higher by 41.71% and 3%, respectively. The temperature characteristics of the modified solar still components were higher than those of the corresponding components of the conventional solar still. Thermodynamic, economic and environmental analysis were also used to investigate the effects of hollow red bricks heights in solar still [12]. The investigation showed that while red bricks generally improve productivity, the productivity improvements at heights of 6, 4, and 8 cm were 33.84%, 29.1%, and 28.87%, respectively compared to the conventional solar still. Additionally, the 6-cm height yielded the maximum energy payback period and could mitigate about 94.26 tons of CO2 over ten (10) years. For detailed reviews of heat storage technologies in solar stills, readers should consult [13-15]. In recent times, however, Shankara Narayanan and Murugan [14 - 15] identified bio-wastes as alternative SHS materials, offering robust, sustainable, cost-effective, and economic benefits with minimal environmental impact.

Numerous researchers have investigated the impact of bio-based materials for performance enhancement in solar stills [11], [14 - 21]. In the summer season in Ongole, India (15.5057 °N, 80.0499 °E), Dhivagar et al. [15] used conch shell biomaterial as both an energy storage material and a porous material to enhance the productivity of a passive solar still, and performed economic and environmental analyses. In their work, sixty pieces of conch shell of almost equal size were collected, washed clean, dried, painted black, and spread in the solar still basin. The experimental investigations were evaluated using cumulative yield, energy, and exergy efficiencies relative to a conventional type. The results showed that the cumulative yield and the energy and exergy efficiencies of the modified solar still exceeded those of the conventional solar still by 10.8%, 10.3%, and 9%, respectively. The economic and environmental analysis also indicated that the cost per litre (CPL) of the distillate and CO2 mitigation of the modified solar still were enhanced by 11.1% and 10.9%, respectively. The modified solar still achieved these results because the calcium carbonate in the shell absorbed, stored, and released solar thermal energy during low-sunshine hours. The porous surface, on the other hand, acts as an effective solar absorber. The heat-transfer mechanism of calcium carbonate helps maintain a consistent evaporation rate, while its porosity increases water temperature, thereby increasing the evaporation rate. In a similar work, Nair et al. [16] investigated the effect of black-coated conch shells and a glass-coated heat-absorbing substance, chlorophyll pigment, in a single-slope passive solar still. Three similar solar stills were fabricated: (a) black-coated conch shells with a chlorophyll-pigment-coated glass cover; (b) uncoated conch shells with a chlorophyll-pigment-coated glass cover; and (c) uncoated conch shells with a glass solar still. Results of the investigation showed that coating the glass cover with a heat-absorbing material alone could increase productivity by 60%. Compared with a conventional type, painting the shells black produced a 25% increase. These improvements could be due to the high thermal conductivity (2.7 W/m. K) of the conch shell containing $CaCO_3$. The pH value of the distillate was between 6.8 and 7, the water hardness was 298 mg/L, and the conductivity was 10.1 .All these values are within the World Health Organization (WHO) standards, thereby justifying the safety of the distillate. Again, Dhivagar et al. [14] also employed a bio-waste, Snail shells, to enhance the productivity of a single slope passive solar still in India. Shells were found to increase the basin's water temperature, evaporation rate, and productivity. The cumulative distillate, the energy and exergy efficiencies of the modified unit compared to a conventional type, were 4.3%, 4.5%, and 3.5%, respectively. Economically, the CPL was 3.4% higher than that of the CSS, but it's payback time was 6 days shorter. Environmental analysis also revealed that CO_2 mitigation and the carbon credits earned were higher than those of the CSS. Noman et al. [17] also evaluated the productivity, energy efficiency, exergy efficiency, and economic analysis of a tubular solar still integrated with 5 mm average-sized macro Pistachios shell particles as a sensible heat energy storage material. The results showed that the solar still's productivity increased by 27.3% and its energy efficiency increased by 47.96%. The maximum exergy efficiencies for the modified unit and the conventional unit were 3.83% and 2.22%, respectively. Economically, CPL improved by 12.903% and payback time decreased by 13.515%. In a similar work, Noman et al. [18] used a smaller particle size of the same shell, i.e., a powder with an average particle size of 1.5 mm. They reported improvements in productivity and payback time of 46.26% and 24.66%, respectively. The thermal and exergy efficiencies were 22.26% and 1.98% for the modified solar still, and 16.86% and 1.35% for the conventional solar still. In India, Balachandran et al. [19] used Egg shells as a sensible heat storage material in a single-slope solar still. Their findings indicated improved yields of 18% and 26.07%, and improved thermal efficiencies of 18% and 26.07% compared to a conventional solar still. In another work, using custard apple seeds (CAS) as a bio-waste material, Noman et al. [20] investigated the freshwater productivity, energy, and exergy efficiencies in a tubular solar still (TSS). The economic viability, environmental impact, and sustainability of the bio-waste-integrated solar still compared with a conventional type, were also examined. Their findings indicated a 52.24% increase in daily yield and improvements of 60.69% and 87.37% in the energy and exergy efficiencies, respectively. There were also noticeable improvements in both economic and environmental analyses. A 33.33% higher CPL and 45.73 fewer days of PBT, were recorded. The CO_2 mitigation, net carbon emission mitigation over a 10-year lifetime, and carbon credit earned were 34.96 kg/year, 4.42 tons, and $48.18 more than the corresponding values for the conventional type, respectively.

As noted in the previous paragraphs, many studies have demonstrated that sensible energy storage materials can improve the productivity of solar stills. Among them are rocks, charcoal, sand, oil palm shells, and agricultural waste. It has been reported that these materials are capable of increasing the basin water temperature and yield. Omani rock stone bed enhanced the distillate yield of a solar still by 18.6% [8], charcoal-filled cylinder had up to 43.33% enhancement compared to a traditional type [9], etc. Kabeel et al. [10] enhanced a conventional solar still by 129% using sand as a sensible heat source. The daily production of the modified unit and the conventional type were 2.75 kg/m2 and 1.2 kg/m2, respectively. Oil palm shells at different masses have also been noted to increase the yield of a conventional solar still. The temperature characteristics of the components of the oil palm shells assisted solar stills were consistently higher than the corresponding components of the conventional type [11]. Other low-cost, natural waste-derived sensible heat storage media capable of enhancing the productivity of solar stills include conch shell [15] [16], snail shell [14], pistachio shell [17] [18], eggshell [19], etc. These shells, like the periwinkle shell, contain a high amount of calcium carbonate($CaCO_3$), a compound that has been found capable of absorbing heat and radiation from the atmosphere and releasing it to the immediate environment at low solar intensity [21]. However, despite these seashell animals, especially in coastal and mangrove ecosystems that face surface-water contamination from oil activities, their potential as a stable and eco-friendly thermal storage material in solar desalination systems remains unexplored, as with other shells.

2.1. Motivation for the current study

Past studies have shown the potential of using crustacean and mollusc shells as sensible heat storage materials to boost the productivity of solar stills [11], [14 - 19], [21 - 26]. These wastes, especially those from food processing, can cause serious environmental and health problems due to their limited direct application [23]. Nevertheless, they have been found to contain some amount of chitin/chitosan, which are useful in various applications such as water purification [24], metal uptake from wastewater [24 - 26], bio composites [26], solar desalination [27], etc. In particular, periwinkle (Tympanotonos fuscatus), a marine gastropod, is consumed in large quantities in Nigeria, especially in coastal and mangrove ecosystems. Its consumption produces residual shells, thereby posing a threat to the environment; managing it has become a major challenge because of the high daily production of this waste. Specifically, in Delta and Rivers States, Nigeria, about 40.3 tons of periwinkle are harvested annually [28]. In these areas, it has been noted that oil activities contaminate most surface water, leading to the presence of several heavy metals at high concentrations and low pH values below the WHO standard [29]. Elemental analysis showed that the shell powder contained a high amount of calcium carbonate ($CaCO_3$), with calcium oxide (CaO) as the most dominant oxide at about 81.8%. Other prominent metal oxides found in the shell are shown in Table 1 [25]. The majority of these synthetic oxides, such as Al_2O_3, Fe_2O_3, MgO, and SiO_2, have been found useful in solar stills, either as nanoparticles, nanofluids, nanopaints, and/or nano-enhanced materials [30]. Additionally, Fourier-transform infrared(FT-IR) spectra revealed a weak band at 1785.4 cm-1 and two prominent peaks at 1468.6 and 857.3 cm-1, confirming the presence of calcium carbonate, as shown in Figure 1 [25]. These peaks are also similar to the peaks of other shells, such as eggshell [31], snail shell [32], and calcium oxide nanoparticles (CaO–NPs) synthesized from periwinkle shell [33]. Calcium carbonate, according to Gane et al. [21], can absorb heat and radiation from the atmosphere and release the same to the immediate environment at low solar intensities; therefore, shells containing this compound can serve as cost-effective, eco-friendly and sustainable energy storage materials, particularly in low–temperature thermal systems such as solar stills and crop dryers. Thermal characteristics have also shown that the average thermal conductivity of a pelletized powdered periwinkle shell was 18 W/mK [25]; a value higher than pure CaO (=15 W/mK), Conch shell (= 2.7 W/mK), and other pure metal oxides like SiO_2 (= 1.7 W/mK) and TiO_2 (= 9.2 W/mK) [25]. Again, structural characteristics also revealed non-uniform particle sizes between 2 and 34 μm, rough surfaces, and porous appearance in the internal structure [25][32]. The calculated average porosity was 59%, and the maximum wavelength of UV absorption was 239 nm, indicating high absorption potential for surface applications and the ability to absorb light in the UV range, respectively [33]. To date, unlike other shells, the periwinkle shell has not been investigated for use in solar stills in any form, to the best of the author's knowledge. In this work, three key performance parameters, vis-à-vis, productivity, energy, and exergy efficiencies, were investigated using two similar single slope passive solar stills: a conventional solar still (CSS) and a Periwinkle shell assisted solar still (PWSASS) under the same climatic conditions at Nsukka- Nigeria (lat. 6.87°N and long. 7.38°E). In addition, the qualities of the feed water (stream water) and the distillate were examined.

Table 1. Prominent metal oxides found in the periwinkle shell [25]

Metal oxide chemical formula	Concentration (wt.%)
CaO	81.803
SiO_2	6.734
MgO	3.069
Al_2O_3	2.548
Fe_2O_3	2.380
SO_3	1.001
P_2O_3	0.752
SrO	0.508

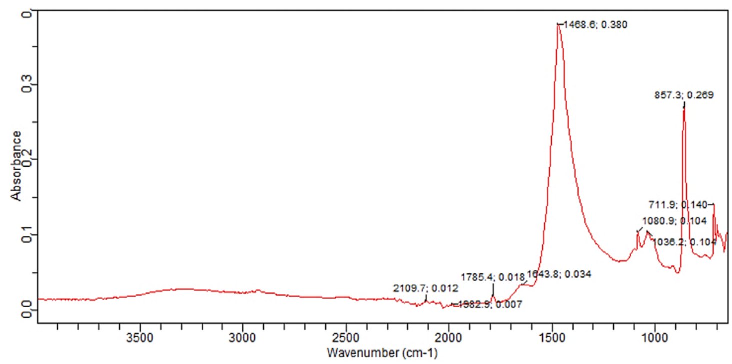

Figure 1. FTIR spectra of periwinkle shell powder [25]

3. Materials and methods

3.1. Description of the periwinkle shell-assisted solar still

The simplest and most cost-effective solar still is the single-slope passive design. It comprises a transparent glass cover that allows solar radiation to penetrate the water basin, thereby increasing the basin's water temperature and facilitating evaporation. In this study, two identical single-slope passive solar stills were used. The solar still is made from a mild steel plate 1.6 mm thick. The bottom area is 0.2 m^2, and fiberglass of 5 mm thickness was used as the insulation to reduce heat loss to the environment. To increase the absorption of incident solar energy, the interior surfaces of the plate were painted black. For more information on the technical details of the solar still, the reader should consult [34]. One of the solar stills lacks a periwinkle shell and is classified as the conventional solar still (CSS), while the other contains periwinkle shells and is classified as the periwinkle-shell-assisted solar still (PWSASS). Figure 2 shows the sixty (60) pieces of black-painted periwinkle-shell bio-waste evenly spaced on the bottom of the PWSASS basin. As already noted in the previous section, periwinkle shell, like other seashells, contains a high amount of calcium carbonate that is capable of absorbing heat and radiation from the atmosphere, and releasing the same to its immediate environment at non-sunshine hours [21]. In addition, the periwinkle shell contains additional metal oxides that have been found to increase the yield of solar stills. Table 2 presents the thermophysical properties of the periwinkle shell.

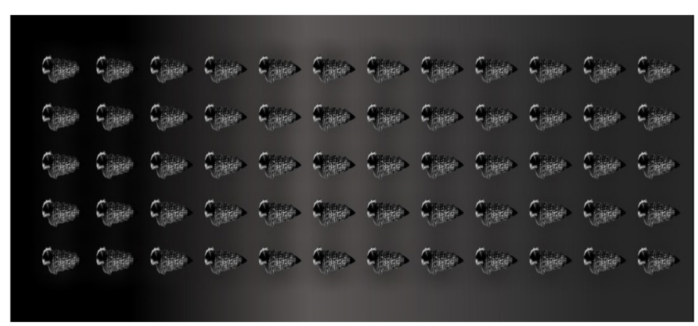

Figure 2. Evenly spread Periwinkle shells on the basin of the PWSASS

Table 2. Properties of the periwinkle shell

Thermal properties	Symbol	Values (unit)	References
Thermal conductivity	k	18 W/mK	[25]
Specific heat capacity (C_p)	c_p	0.93 kJ/kgK	
Mass	m	166.704 g	
Porosity[a]	%	59%	[33]
Porosity[b]	%	20%	

a: theoretical value; b: experimental value

3.2. Experimental setup

The experimental observations were carried out at the National Centre for Energy Research and Development, University of Nigeria, Nsukka (lat. 6.87 °N and long. 7.38 °E). The two solar stills were positioned facing south to receive the maximum amount of solar radiation. An equal water mass of 1 kg of the feed water obtained from the stream was poured into each of the solar stills, and K-Type thermocouple wires connected to an 8-channel Temperature Meter, Applent AT 4208 model, were used to measure the ambient, the glass, and the basin water temperatures every hour. The distillate yields were also measured hourly using calibrated 100 ml flasks. Weather variables, such as solar radiation data, were obtained from the weather station at the National Centre for Energy Research and Development, University of Nigeria, Nsukka. To ensure the repeatability of the experimental data, two experimental runs were performed between 9:00 and 18:00 on two consecutive days with equal water mass, and minor deviations were observed. Therefore, a single experimental run under specific conditions was used to interpret the system's performance. Figure 3 shows the schematic diagrams of the CSS and PWSASS solar stills. The PWSASS consists of a black-painted mild steel basin containing the saline/stream water and black painted periwinkle shells of uniform sizes. These shells are uniformly distributed at the base, and the solar stills are perfectly insulated to minimize heat losses. Solar radiation passes through the transparent glass cover, heating the basin water and promoting evaporation. The evaporated vapor condenses on the inner glass surface and flows into the distillate outlet channel for collection. The glass, basin water, and ambient temperature were measured with the K-type thermocouple sensors.

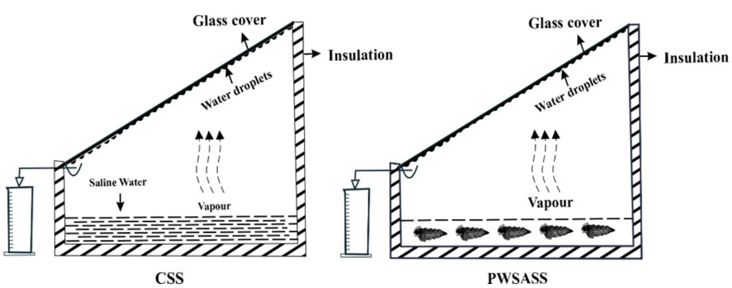

Figure 3. Schematic diagrams of the CSS and PWSASS

3.3. Uncertainty analysis

According to the Joint Committee for Guides in Metrology [35], every measurement is an approximation to the real or reference value, unless the value is reported with an uncertainty statement. An uncertainty statement is a parameter that characterizes the dispersion of the values that could be attributed to the measurand, i.e., an output quantity. The uncertainty statement removes doubt and indicates the precision and/or completeness of the output quantity. In this work, the sources of uncertainty come from the measuring instruments such as the thermocouple sensor, graduated cylinder, and pyrometer. Assuming the measurements from these instruments are uniformly distributed, the type (B) method of calculating uncertainty was adopted as given in equation (1) [35]. According to the method, the standard uncertainty of each of the instruments is related to the its accuracy as given in equation (1). The accuracies, ranges, and the standard uncertainties of the measuring instruments are as shown in Table 3.

$$u = \frac{a}{\sqrt{3}} \quad (1)$$

Where u and a represent the uncertainty of the data and the accuracy of each instrument, to evaluate the uncertainty associated with the yield of a solar still, the uncertainty propagation law given in equation (2) is used.

$$u(y) = \left[\left(\frac{\partial y}{\partial x_1} \times u_1\right)^2 + \left(\frac{\partial y}{\partial x_2} \times u_2\right)^2 + \ldots + \left(\frac{\partial y}{\partial x_n} \times u_n\right)^2\right]^{\frac{1}{2}} \quad (2)$$

where y, $x_1 \ldots x_n$, $u_1 \ldots u_n$ and u(y) are the desired experimental output, measured independent parameters, standard uncertainties of the independent parameters, and the standard uncertainty of the desired output, i.e., the yield of the solar still in this case. In contrast, the number of independent parameters is denoted by the letter 'n'.

Table 3. Accuracies, ranges, and standard uncertainties of measuring instruments

Instrument	Accuracy	Range	Standard uncertainty (u)
Pyrometer	1 W/m^2	0 – 5000 W/m^2	0.6 W/m^2
Thermocouple sensor	0.1 °C	-50 °C – 999.9 °C	0.06 °C
Graduated cylinder	± 2 ml	0 – 100 ml	1.15 ml

3.4. Theoretical analysis

3.4.1. Energy Analysis

Two thermodynamic analyses, i.e., energy and exergy efficiencies, were used in this study to examine the thermal behaviour of the solar stills. These are the energy and exergy efficiencies. The energy efficiency is the analysis based on the first law of thermodynamics. On the other hand, the exergy efficiency is the analysis based on the second law of thermodynamics. Energy efficiency in a solar still is the ratio of the output energy based on the freshwater yield to the input energy from solar radiation, expressed as a fraction. It can be instantaneous, i.e., efficiency on an hourly basis, or overall energy efficiency, which is the summation of the instantaneous efficiencies over a time duration, such as daily. It is a measure of the effectiveness of how solar still converts solar radiation into freshwater, and the hourly and overall efficiencies can be calculated as given in equations (3) and (4), respectively [5][36].

$$\eta_{hr} = \frac{\dot{m}_{evp} \times \lambda_{fg}}{(I_s(t) \times A_{ab}) \times 3600} \quad (3)$$

$$\eta_{overall} = \frac{\sum \dot{m}_{evp} \times \lambda_{fg}}{\sum (I_s(t) \times A_{ab}) \times 3600} \quad (4)$$

where $\dot{m}_{evp}$ is the hourly yield in kg, λ_{fg} is the latent heat of vaporization of water in J/kg, whose relation with basin water temperature (T_w) in (°C) is as given in equation (5), where is the solar radiation intensity, in W/m^2, and A_{ab} is the absorber area of the solar still, in m^2.

$$\lambda_{fg} = 1000 \times \begin{bmatrix} 2501.9 - 2.40706 \times T_w + 1.192217 \times 10^{-3} \times \\ T_w^2 - 1.5863 \times 10^{-5} \times T_w^3 \end{bmatrix} \quad (5)$$

3.4.2. Exergy analysis

Based on the second law of thermodynamics, the exergy efficiency evaluates the useful energy of thermal systems, i.e., the maximum work a system can deliver as it approaches thermodynamic equilibrium with its environment. Unlike the energy efficiency, it gives more information concerning the thermal performance of a system. Equations (6), (7), and (8) are the equations used to calculate the instantaneous exergy output, input, and exergy efficiency in a passive solar still, respectively [37].

$$Ex_{out} = \frac{\dot{m}_{evp} \times \lambda_{fg}}{3600} \times \left(1 - \left[\frac{T_{amb}}{T_w}\right]\right) \quad (6)$$

$$Ex_{in} = A_{ab} \times I_s \times \left[1 - \frac{4}{3} \times \left(\frac{T_{amb}}{T_s}\right) + \frac{1}{3} \times \left(\frac{T_{amb}}{T_s}\right)^4\right] \quad (7)$$

$$\psi_{hr} = \frac{Ex_{out}}{Ex_{in}} \quad (8)$$

where T_s, T_{amb} and T_w are the temperatures of the Sun (assumed 6000 K), ambient water, and basin water in kelvin, respectively. Other parameters are the hourly yield, $\dot{m}_{evp}$ in kg, latent heat of vaporization of water, λ_{fg} in J/kg, solar radiation intensity, I_s in W/m^2 and area of the absorber, A_{ab} in m^2.

4. Results and discussion

4.1. Ambient and solar radiation characteristics

The ambient and solar radiation characteristics on a typical experimental day are shown in Figure 4.

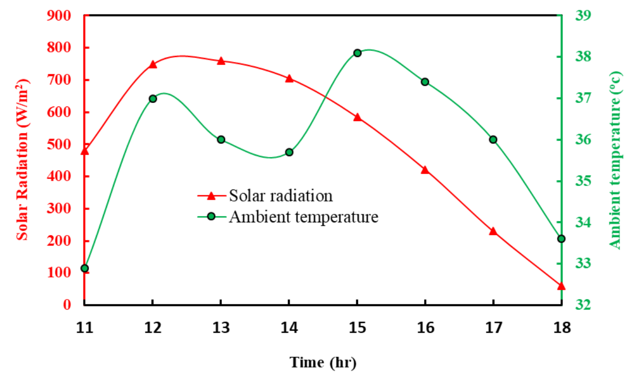

Figure 4. Variations in ambient temperature and solar radiation over time

The figure showed that the solar radiation rises gradually from 480 W/m^2 at 11:00, peaks at 12:00 with 748 W/m^2 before it slowly diminished to 61 W/m^2 at 18:00. The ambient temperature on the other hand, unlike the solar radiation had two peaks; the first peak coinciding with the peak of the solar radiation at 12:00 with 37 °C, and the final peak at 15:00 with 38.1 °C before it gradually decreased to its lowest value (33.6 °C) at 18:00. The peak ambient temperature was 38.7 °C. The least was 33.6 °C at 18:00. It could be inferred that as the solar radiation increases, the ambient temperature increases as well. However, due to the prevailing weather conditions on the experimental day, the ambient temperature fluctuated between 13:00 and 14:00.

4.2. Temperature variations of the major components of the solar stills

Figures 5 and 6 represent the glass and the basin water temperature variations with time, respectively. The temperature of these components plays a vital role in the performance of solar stills, particularly in creating a temperature difference to facilitate condensation. While the basin water temperature influences the evaporative rate, the glass temperature influences the condensation rate.

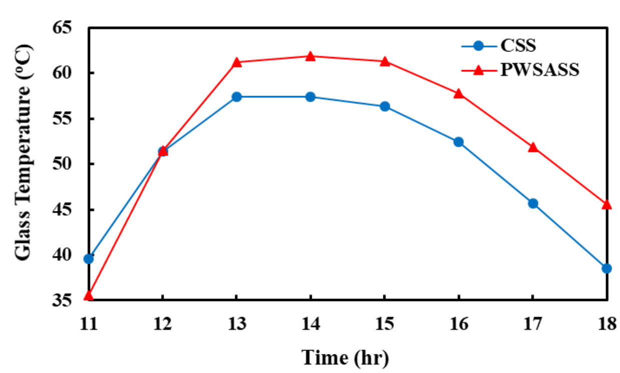

Figure 5. Glass temperature variations with time

As shown in Figure 6, both temperatures followed a similar trend with solar radiation, mainly due the its influence on the performance of solar thermal devices such as solar stills. The two temperatures rose together until coinciding at the peak solar radiation at 12:00, before being separated. However, due to the specific heat capacity of the glass, its gained energy enabling its peak time to differ from that of the solar radiation, notably between 13:00 and 14:00. Again, it could also be observed that before 12:00, the glass temperature of PWASSS is lower than that of the CSS, however, the reverse becomes the case after that time until the end of the experiment. The reason for this may be the increasing rate of evaporation in the presence of periwinkle shells, because periwinkle shells contain calcium carbonate, which is capable of absorbing heat and radiation from the atmosphere and releasing it to the immediate environment [21]. The highest recorded temperature for the PWSASS was 61.9 °C at 15:00, while the corresponding temperature for the CSS was 57.4 °C between 13:00 and 14:00. The minimum glass temperatures for the PWSASS and CSS at 18:00 were 45.6 °C and 38.5 °C, respectively. Noticeable also is the increasing divergence between the glass temperatures from the onset to the end, signifying the influence of the PWSASS in increasing the evaporation process. The temperature difference between the glass temperatures at 13:00 is 3.8 °C, while at 18:00 it increased to 7.1 °C.

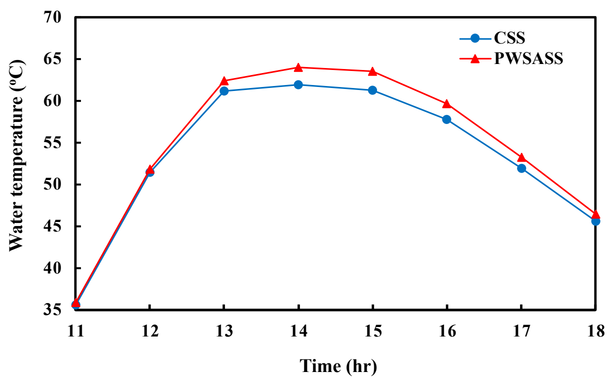

Figure 6. Water temperature variation with time

Figure 7 shows the basin water temperature variations with time. Like the glass temperature, the basin water temperature also followed similar trends to solar radiation, and the peak basin water temperature differs from the peak solar time due to the energy gained by the water mass. The temperatures rose together, reaching the peak at solar noon(12:00) before separating. However, unlike the glass temperatures, the difference between the two basin water temperatures was slight, as they tended to converge towards the end of the experiment. This may be due to decreased energy absorption by PWS as solar radiation decreases. Nevertheless, after the peak solar time, the basin water temperature of the PWSASS remains higher than the corresponding temperature of the CSS. The highest recorded basin water temperature for the PWSASS was 64 °C, while the corresponding temperature for the CSS was 61.9 °C. The continued higher temperatures of the PWSASS basin water attest to the fact that energy storage materials like PWS can enhance the evaporative process.

4.3. Productivity of the solar stills

Besides temperature characteristics, the hourly and cumulative yields of solar stills are other important measures of their performance. They measure the effectiveness of the two primary heat transfer mechanisms in a solar still, i.e., evaporation and condensation. Figure 7 shows graphs of the hourly and cumulative yields of the PWSASS and CSS over time.

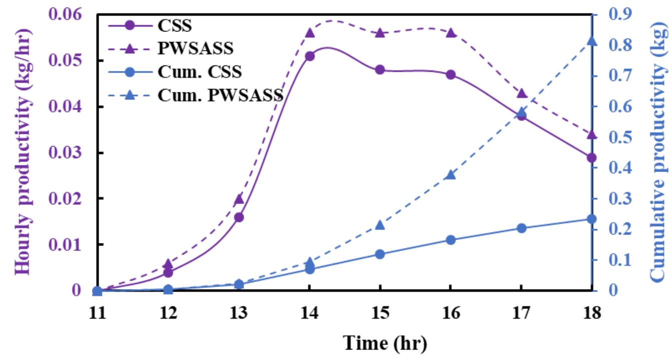

Figure 7. Hourly and cumulative yield variation against time

From the figure, it can be seen that high distillate yield was produced by both stills between 14:00 and 16:00, due to the increasing evaporative rate under high solar radiation. Additionally, during the period, the PWSASS maintained the highest yield of 0.056 kg/hr, while the CSS recorded the highest yield of 0.051 kg/hr at 14:00 only. At low solar radiation levels, the yield decreases instead. Meanwhile, throughout the duration, both the hourly and the cumulative yield of the PWSASS superseded that of the CSS. The cumulative yield of the CSS was 0.233 kg/day, and the PWSASS was 0.817 kg/day, representing more than 250% of the CSS yield. The daytime and overnight yields of the solar stills are shown in Figure 8. The figure showed that the daytime and overnight time yields of the PWSASS were 15.72% and 3.64% higher than the CSS. The higher yield during the daytime than at night may be due to decreasing solar radiation as the sun sets. The higher yield of the PWSASS was mainly due to the increased evaporative rate caused by the presence of periwinkle shells, which are capable of releasing absorbed solar radiation to increase the evaporative rate and yield. Table 4 shows the yields, thermophysical parameters of biomaterial-assisted solar stills in the literature and the present study. As shown in Table 4, the yield of our PWSASS (1.61 kg/m^2) is lower than that of other bio-materials-assisted solar stills, whose yields range from 2.04 to 2.72 kg/m2. Specifically, for similar solar stills (i.e., conventional solar stills), Dhivagar et al. [15] reported 2.35 kg/m^2 daily yield using conch shells, and Balachandra et al. [19] reported 2.46 kg/m^2 using Egg shells. The daily yields of Snail and Crab shells were 2.28 and 2.04 kg/m^2 as reported by Dhivagar et al. [14] and Mohan et al. [38], respectively. The lower yield may be attributed to a number of material, experimental, and environmental factors. Variations on these parameters strongly influence solar still performance, underscoring the need for standardized testing protocols. Nevertheless, it is essential to note that the daily yields of our PWSASS outperformed our CSS type by 13.38%.

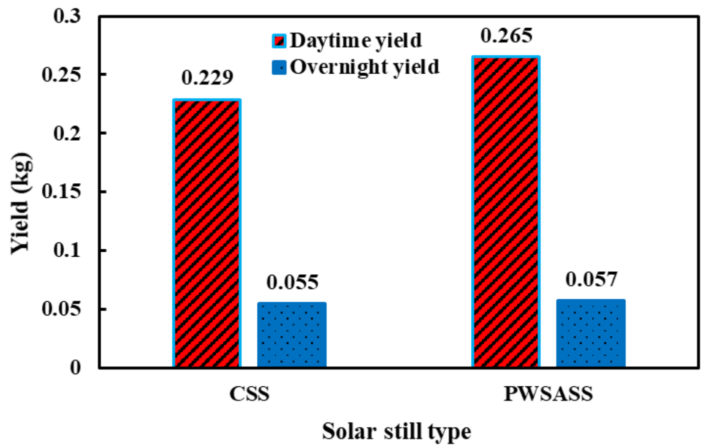

Figure 8. Day and overnight time yield of the solar stills

Table 4. Yield and thermo-physical properties of solar stills assisted bio-wastes used in solar stills

S.No	Country/coordinate	Type	Material	Selected thermo-physical properties			Water yield	Ref.
				C_p (kJ/kgK)	k (W/mK)	Porosity (%)	(kg/m^2)	
1.	India (15.51°N, 80.05°E)	CSS	Conch shells	0.37 – 0.4	5.1	41.2	2.35	[15]
2.	India (9°41'N, 77°57")	CSS	Egg shells	0.84	5.526	20	2.46	[19]
3.	Indonesia (3°33", 99°39',	DSSS	Oil palm shells	1.54	0.32	-	2.68	[39]
4.	India (15.5°N, 80.04 °E)	CSS	Snail shells	0.32 – 0.36	4.8	48	2.28	[14]
5.	India(12 °N, 80 °E)	TSS	Pistachio shells	1.894	0.231 – 0.466	15.2	2.41	[17]
6.	India (12 °N, 80 °E)	TSS	Pistachio shell powder	1.894	0.231 – 0.466	15.2	2.72	[18]
7.	India (n.a)	CSS	Crab shells	1.2 – 2.0	0.3	-	2.04	[38]
8.	Nigeria (6.87°N, 7.38 °E)	CSS	Periwinkle shells	0.93	18	20	1.61	Present study
9.	Nigeria (6.87°N, 7.38 °E)	CSS	Non-periwinkle shells	-	-	-	1.42	Present study

4.4. Energy and exergy analysis

Figure 9 shows the hourly variations in the energy and exergy efficiencies of the PWASS and CSS. It could be seen from the graph that the instantaneous energy efficiencies are always lower than the corresponding energy efficiencies. Both parameters fluctuate over time, with maximum exergy efficiencies at 14:00(1.53%)and 16:00(2.25%)for the CSS and PWSASS, respectively, likely due to high solar intensity. On the other hand, the maximum energy efficiencies occurred at 18:00 with 48.92% for PWSASS and 41.77% for CSS. Again, before 14:00, probably at 13:00, the energy and exergy efficiencies of the CSS superseded those of the PWSASS, owing to thermal inertia in the PWSASS, as the periwinkle shell absorbs solar energy first. The higher values of energy efficiencies compared to exergy efficiencies are based on the exergy concept, i.e., the degradation of energy quality due to irreversibilities. In thermal systems, energy losses associated with converting solar energy to heat are unavoidable. Again, with reference to the ambient temperature and basin water temperature, the instantaneous exergy efficiency is always lower than the corresponding energy efficiency because of the associated lower evaporative thermal energy (see equation 6). This trend is also similar to the results obtained in a theoretical study by Ranja et al. [40] and in an experimental survey of Al-hamadani and Shukla [41].

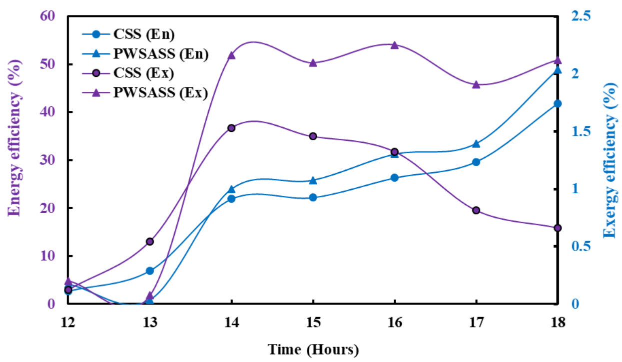

Figure 9. Energy and exergy efficiencies of the solar stills against time

4.5. Water quality test result

The water test results of the distillate and the stream water are presented in Table 5. These results were also compared with the World Health Organization(WHO)quality assessment standards, using the benchmarks provided by WHO. It is worth noting that the pH level and total dissolved solids(TDS)are within the WHO benchmarks. The results also showed that the total coliform, faecal coliform, and arsenic levels were significantly reduced to zero. Therefore, the distillate meets WHO standards.

Table 5. Parameters of the water test

Parameter	Stream water	Distillate	WHO Standard
pH	5.8	6.9	6.7 – 8.5
Turbidity	7.6	2.1	< 5 NTU
TDS	99.79	49.15	50 g/l
Total Coliform	56	0	0
Faecal Coliform	18	0	0
E. Coliform	12	0	0
Arsenic	0.2258 ppm	0.000	0.010 ppm
Chromium	0.5250 ppm	0.1750 ppm	0.050 ppm

5. Conclusion

In this study, the yield, energy, and exergy analyses of two identical solar stills, one conventional and the other incorporating periwinkle shells, were performed and compared under similar climatic conditions in Nsukka, Nigeria (lat. 6.87° N, long. 7.38° E). In the periwinkle shell-assisted solar still, the shells were evenly spread across the basin to serve as a sensible heat energy storage medium. Findings from the temperature characteristic of the major components showed that the temperatures of the PWSASS exceeded those of the CSS counterparts. The overall yield of the PWSASS was also higher than the CSS, while the day and night time yields of the CSS and PWSASS were 0.229 kg and 0.055 kg, and 0.265 kg and 0.057 kg, respectively, representing a 13.38% enhancement in cumulative yield. The energy and exergy efficiencies of the periwinkle shell-assisted still were also higher, 48.92% and 41.77%, respectively, compared to 2.25% and 1.53% for the conventional still. Additionally, water quality tests also showed that the total coliform, faecal coliform, and arsenic levels of the distillate were significantly reduced to zero, while the pH level and total dissolved solids (TDS) are within the WHO benchmarks. The above results indicate the capacity of using periwinkle shells as sensible heat storage medium to enhance the distillate yield in solar still. In contrast, the yield of the PWSASS was less compared to other shell-like bio-wastes, which may be due to many factors such as material characteristics, different designs, and environmental conditions. Above factors strongly influence the solar still performance, thus the need to undertake standardized testing protocols. Nevertheless, it is important to note that the daily yields of our PWSASS outperformed the CSS type by 13.38%, likely due to the high calcium oxide (CaO) content, fine particle morphology, and heat-retention ability. Therefore, harnessing the abundant local waste material with good thermal properties, this study contributes a practical, low-cost pathway for sustainable solar desalination in resource-constrained environments, addressing both environmental waste management and renewable energy performance improvement. It also limits the use of other techniques, such as phase change materials(PCMs), nanoparticle-enhanced fluids, extended surfaces, and reflective concentrators, for thermal storage to improve heat transfer. These materials are not only expensive but also poses environmental concerns and are not easily accessible in resource-limited settings.

6. Future scope of work

In this study, the capability of a bio-waste, periwinkle shell has been investigated as a low-cost energy storage medium for solar still enhancement. Nevertheless, the investigation was limited to a water mass of 1 kg and 60 pieces of periwinkle shells, which may not be the optimal conditions. Therefore, it is important to investigate the influence of the shell particle size, micro- to nanoscale, and thermodynamic performance on different water and shell mass. The above investigations could help to determine the optimal conditions that are capable of enhancing heat transfer rate and maximizes evaporation efficiency. Additionally, composite forms could as well be investigated especially when blended with other bio-wastes or metal oxides. The blends may enhance the energy storage capacity and thermal stability. It is also necessary to carry out comparative investigations, economic and environmental assessment involving other bio-waste-derived materials and the shell.

Nomenclature

Symbols

A	Area
a	Accuracy
m	mass
T	Temperature

t	Time
u	Standard uncertainty
I_s	Solar radiation intensity
x	Measured independent parameter
y	Desired experimental output
$\dot{m}$	Hourly yield
u(y)	Standard uncertainty of the desired output
%	Percentage
pH	Potential of hydrogen
Ex_{in}	Exergy input
Ex_{out}	Exergy output
ψ_{hr}	Exergy efficiency
Al_2O_3	Aluminium oxide
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CaO-NP	Calcium oxide nanoparticle
CO_2	Carbon dioxide
Fe_2O_3	Iron (II) oxide
MgO	Magnesium oxide
P_2O_3	Diphosphorus Trioxide
SiO_2	Silicon oxide
SO_3	Sulphur trioxide
SrO	Strontium oxide

Greek symbols

c_p	Specific heat capacity
k	Thermal conductivity
λ_{fg}	Latent heat of vaporization of water

Subscripts and Superscripts

ab	absorber
amb	Ambient
evp	Evaporative rate
hr	Hourly
n	Number of independent parameters
in	Input
out	Output
s	Sun
w	water

Abbreviations

CPL	Cost per litre
CSS	Conventional solar still
FT-IR	Fourier-transformed infrared
LHSM	Latent heat storage material
PWSASS	Periwinkle shell-assisted solar still
SEM	Scanning electron microscopy
SHSM	Sensible heat storage material
UV	Ultra violet
WHO	World Health Organization

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