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DEVELOPMENT AND PERFORMANCE EVALUATION OF A SOLAR WATER STILL

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Abstract: The availability of potable water is a necessity for human existence. A simple laboratory scale solar water still capable of holding 75 litres of water has been developed and evaluated. The highest temperature in the solar still occurred at the vapour region and reached up to 66°C. The productivity of the solar still varies with the depth of water in the still. The results of the productivity were 67.4 ml/m^{2}h, 54.2 ml/m^{2}h and 43.4 ml/m^{2}h for depths of 20 mm, 40 mm and 60 mm respectively. The efficiency of the solar still was found to vary with the depth of water in the basin. The highest efficiency obtained for the solar still was 29.1% at a depth of 20 mm. Characterization of water quality before and after distillation in the solar still showed a reduction in chemical and microbiological constituents after distillation which was comparable to standard drinking water. The solar still could be developed at a small-scale workshop at reasonably cheap costs. Further work to improve the productivity of the solar water still is proposed.
Keywords: Solar energy; water still; distillation; water quality; temperature

INTRODUCTION

Supply of potable water is a major problem particularly in developing countries. The problem often faced is that protected or improved sources, such as boreholes and treated urban supplies, can still be contaminated such that microbiologically unsafe water is delivered [1]. Of major concern is the populace dwelling in rural regions of developing countries who do not have access to these improved sources and are at higher health risks as they depend on the natural sources like rivers, streams and springs which are often contaminated. The ability to be able to treat water on a domestic scale will therefore be of immense benefit.

Nigeria lies within a high sunshine belt and solar radiation is fairly well distributed within the country. The annual average total solar radiation varies from 12.6 MJ/m^2-day in the coastal latitudes to 25.2MJ/m^2-day in the far north [2]. This vast amount of solar energy could be utilized in purifying water domestically.

Solar distillation has been largely used in desalination. It involves utilizing solar energy for heating of water to cause evaporation. The vapour produced, then, condenses to produce distilled water. Gomkali and Datta [3] designed a simple solar still with a double-sloped glass cover plate which had an annual average productivity of 2.5 l/m^2-day and at an efficiency of 28%. Naim [4] also devised a single-stage solar desalination spirally-wound module which had maximum distillation efficiency of 34% and with a productivity of 575 ml/m^2-h. Medugu and Malgwi [5] designed and tested a solar still and claimed that the instantaneous efficiency increases with the increase of solar radiation and with increase of feed water temperature. Tarawneh [6] studied the effect of water depth on the performance evaluation of a solar still and stated that decreased water depth has a significant effect on increased water productivity, noting that the productivity of the solar still is strongly dependent on the climatic, design and operational conditions. Ighodalo and Ebhodaghe [7] also carried out a performance evaluation of a solar still for salty water desalination which produced 0.51 litres/day.

Furthermore, Eze et al. [8] distilled Lagos Bar-beach water using a rectangular still with a single slope inclined to 22° and showed that there was an improvement in water quality of the beach water after distillation. Patel et al. [9] reviewed the methods which can be utilized in improving the performance of solar still to improve productivity. Sathyamurthy et al. [10] investigated the performance of a semi-circular absorber solar still with baffles and reported that the daily yield was higher than conventional still. Ugwuoke et al. [11] evaluated a portable water distillation system and observed that the quantity of distillate water is higher with a higher ambient temperature.

In addition, mathematical modelling and simulation of the solar still have been presented by Adhikari et al. [12], Bemporad [13] and Mowla and Karimi [14]. Medugu and Ndatuwong [15] also carried out a theoretical analysis of heat and mass transfer of water distillation using solar still and concluded that the instantaneous efficiency increased with an increase of both solar radiation and feed water temperature.

There is a need to develop and improve the efficiency and productivity of solar water stills with low cost of production, maintenance and ease of operation. Hence, this study presents the development and evaluation of a simple laboratory scale solar water still with the characterisation of water quality before and after distillation in the still.

DESIGN CONSIDERATIONS

The solar water still consists of a black metallic basin to improve the absorptivity of incident solar energy. The basin holds the water to be purified and is covered with a transparent glass through which solar radiation passes to increase the temperature within the still. The heat transferred to the water still results in an increase in temperature of the water still. The increase in temperature causes steam, or water vapour, to be produced. The steam generated then condenses on the surface of the glass cover on the water still. The condensed water runs along the inclination of the glass cover and is collected in a distillate trough which passes the water into the collecting bottle via a flexible pipe connected to the trough. The metallic basin is lagged using wood. The details of the design of the solar water still and the specifications for the components of the water still designed are described in this section.

Basin

The basin has a square base with a volume of about 75 litres. The dimension of the basin was 600 mm × 500 mm × 250 mm. The black metallic basin was lagged in a wooden frame, 5 mm thick, to prevent heat loss.

Glass Cover

The glass cover is a 3 mm thick transparent glass which is tilted at an angle equal to the latitude of Lagos, Nigeria, to ensure optimum transmission of solar radiation into the still. The angle of inclination of the glass is 6.6° to the horizontal. The elevation will also allow the flow of condensed vapour along the surface of the glass to the distillate trough.

Distillate Trough

The distillate trough is made from a U-shaped polyvinylchloride material which is attached to one end of the basin and at the depressed portion of the glass cover. The distillate trough is connected to the collecting bottle via a flexible pipe attached to the free end of the trough.

Feed Water Inlet

The feed water inlet is located at a height of 140 mm from the base of the basin. The flow of feed water is regulated by a float valve which receives water from a stationary reservoir. The valve is adjustable so as to regulate the level of water in the basin. The experimental set-up of the solar water still is shown in Figure 1.

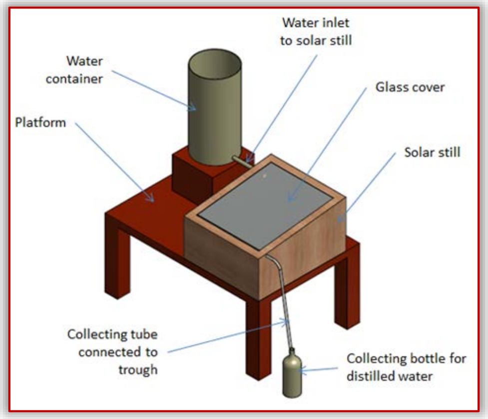


Figure 1. Experimental set-up of the solar water still.

Energy Received by the Solar Still

The energy received daily by the solar still is estimated from the solar radiation intensity, I_s, and the area of the basin, A. ECN and UNDP [2] have noted that the solar radiation intensity around the coastal region in Nigeria is about 12.6 MJ/m^2-day. The energy received by the solar still is therefore, estimated as:

$$E = I_s \times A = 12.6 \times 0.6 \times 0.5 = 3.78\,\mathrm{MJ/day} \quad (1)$$

Distillate Trough

The distillate trough is made from a U-shaped polyvinylchloride material which is attached to one end of the basin and at the depressed portion of the glass cover. The distillate trough is connected to the collecting bottle via a flexible pipe attached to the free end of the trough.

EVALUATION OF THE SOLAR WATER STILL

The solar still was set up and was positioned such that the inclined surface faced the south direction to ensure unhindered reception of solar radiation. The performance evaluation of the solar still lasted 10 hours per day from 0800 to 1800 hours local time. During evaluation, which was carried out between July and September, the height of water in the still was varied and the corresponding results observed were recorded. The heights used were 20 mm, 40 mm and 60 mm, which amounted to 6, 12 and 18 litres respectively. Water from the Lagos lagoon, Nigeria, was utilized in the evaluation of the solar still.

Temperature in the solar still

The temperatures of the water in the still, T_w, and the vapour region between the glass and water, T_g, were measured along with the ambient temperature, T_a, at 30-minute intervals. The temperatures were measured using K-type thermocouples. The positions of the temperature sensors of the thermocouples are indicated in Figure 2.

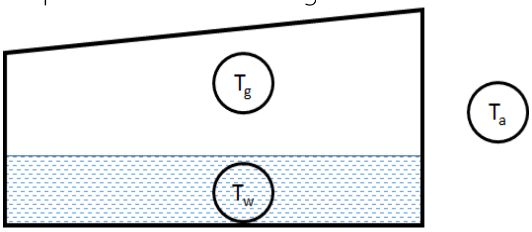


Figure 2. Schematic diagram showing the placement of thermocouples

Productivity of the solar still

The distilled water produced from the solar still collected was measured using a measuring cylinder. This was carried out hourly to determine the hourly production and the cumulative production of distilled water. The productivity of the solar still is the volume of distillate produced per unit area per unit time of operation. Taking V_T as the total volume of distillate and A as the base area of the solar still and t as the time of operation in hours, then the productivity, P, is estimated using Equation (2):

$$P = {}^{V_T}/_{A}\,(\text{per day}) = {}^{V_T}/_{At}\,(\text{per hour}) \quad (2)$$

The term t is the total number of hours of production of distilled water.

Efficiency of the solar still

The heat utilized to evaporate a mass, m_e, of water with volume, V_d, and density, ρ, from the basin can be estimated from the latent heat of vaporization of water, L_v, using Equation (3):

$$Q_e = m_e \times L_v = \rho V_d \times L_v \quad (3)$$

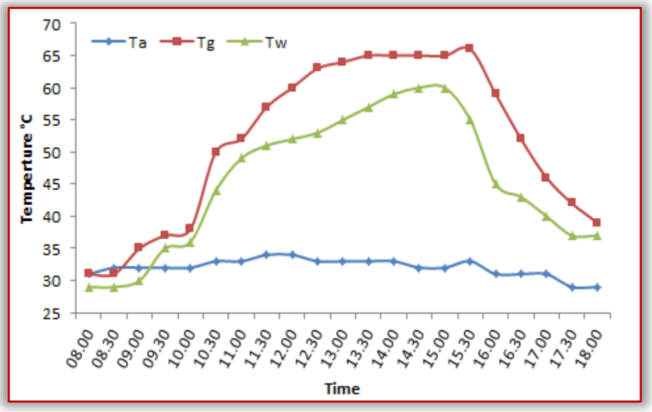
The efficiency of the solar still is a measure of its performance which is calculated from the ratio of energy utilized by the solar still to the energy received by the solar still. The efficiency of the solar still is estimated using [16,17]:

$$\eta_e = {Q_e}/{E} \quad (4)$$

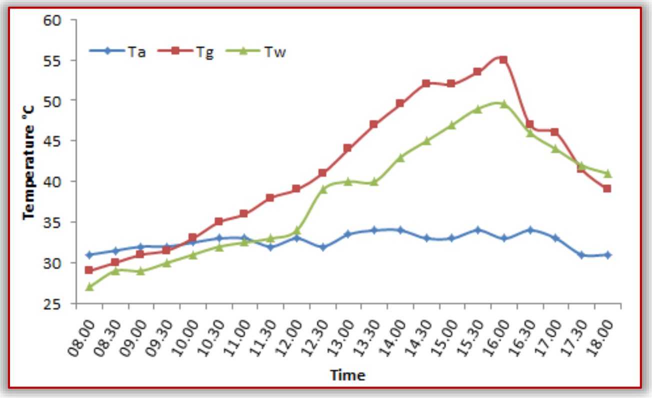
E is the energy received by the solar collector during the period of operation.

Laboratory Analysis

Laboratory tests were conducted to determine the physical, chemical and microbiological properties of water before and after distillation. Laboratory tests conducted determined the pH, conductivity, total dissolved solids, total suspended solids, turbidity, total organic matter, total hardness, nitrate, phosphate, sulphate, copper, iron, manganese, lead and zinc contents of both distilled and untreated water.



(a)



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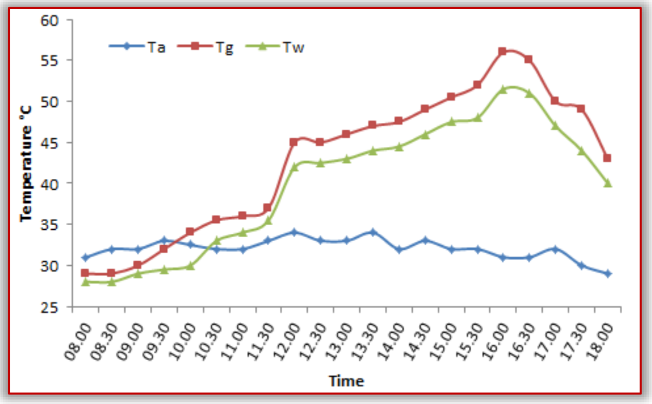
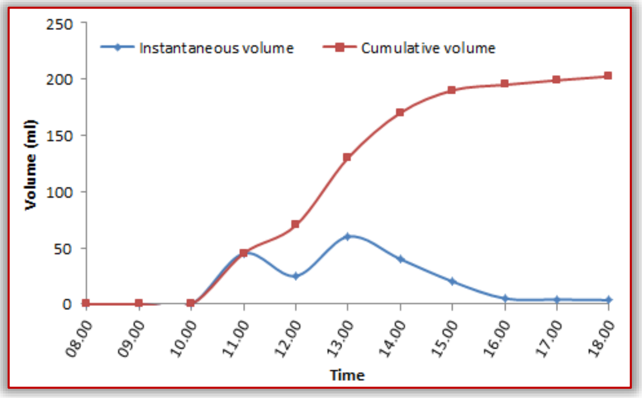


(c)

Figure 3. Variation of average temperature with time in the solar still for different days. a) Day 1; b) Day 2; c) Day 3

RESULTS AND DISCUSSION

Typical daily variation of temperature over time is presented in Figure 3(a)-(c). As was evidently observed, the temperatures within the still were higher than the ambient temperature. The maximum temperature of the vapour region just beneath the glass surface, T_g, ranged from 55°C to 66°C depending on the solar radiation intensity and weather conditions. Lower temperatures, and fluctuations in measurements, were recorded for periods with cloudy weather condition.



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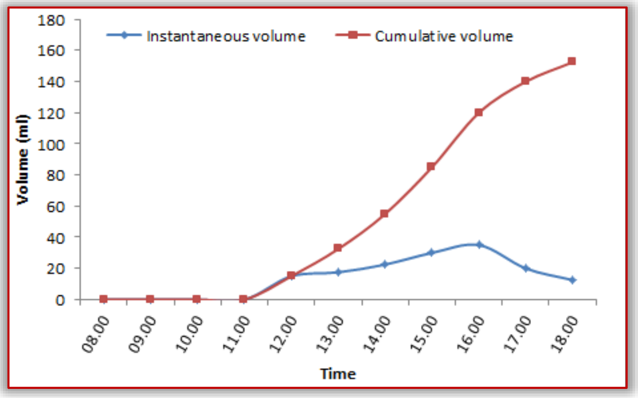

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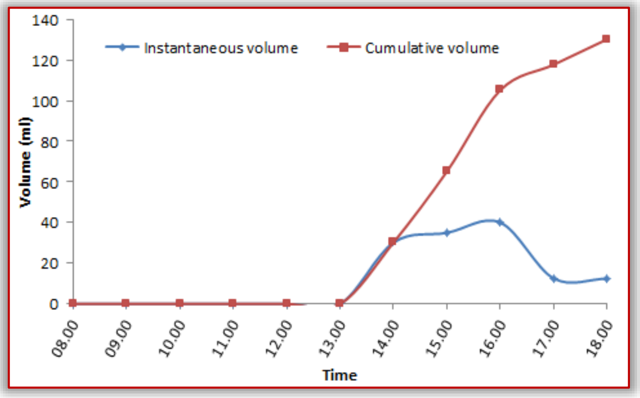
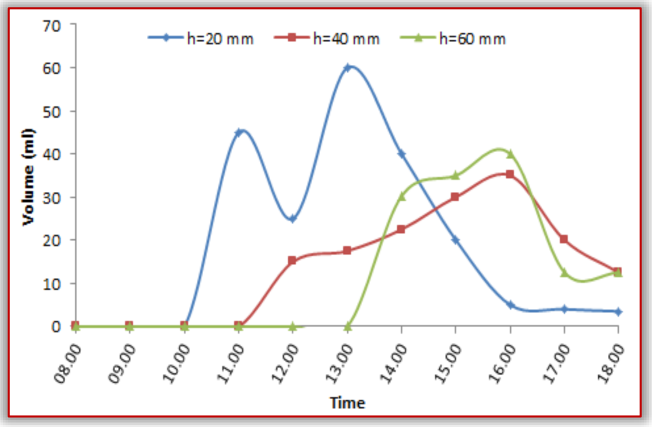


(c)

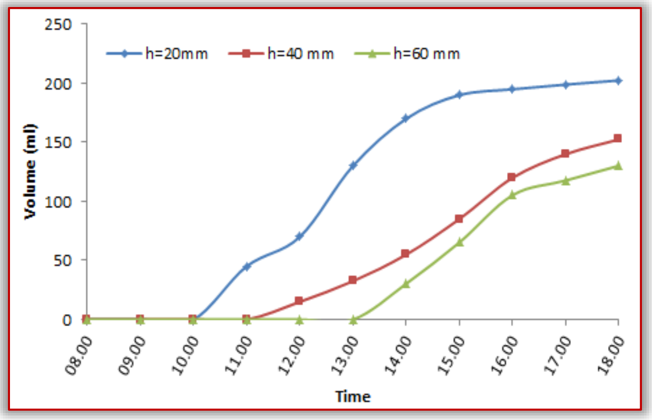
Figure 4. Volume of distilled water collected with time from the solar still at height (a) h=20 mm (b) h=40 mm and (c) h=60 mm

The maximum temperature of water in the basin ranged between 50°C and 60°C. The ambient temperature was between 29°C and 34°C, with the highest temperatures observed between 1200hrs and 1600hrs local time. The temperatures measured are comparable to those obtained by Singh et al. [18] who obtained glass temperatures between 32°C and 49°C and water level temperature ranging from 48°C to 53°C. Badran [19] also observed that the vapour temperature was the highest temperature followed by the water that has been heated in the basin. The range of temperatures obtained from the measurements also correspond to those obtained from studies carried out by Ahsan et al. [20] and Sathyamurthy et al. [10].

The average volume of distillate produced with variation in the height of the water level in the basin is shown in Figure 4(a), (b) and (c) for water level heights, h, of 20 mm, 40 mm and 60 mm respectively. The maximum volume was collected between 1300 and 1600 hours for the different tests and the maximum volume of distillate collected per hour ranged between 35 and 60 ml, depending on the depth of water in the water still.



(a)



(b)

Figure 5. Comparison of (a) instantaneous volume of distilled water collected from the solar still with time (b) cumulative volume of distilled water collected from the solar still with time.

Figure 5 compares the instantaneous and cumulative volumes of water collected over time for the different water depths. It was observed that production of distilled water began earlier between 1000 and 1100 hours when the water level height was 20 mm. Production of distillate started later (between 1100 and 1200 hours) when the height was 40 mm and latest (between 1300 and 1400 hours) when height was 60 mm.

Figure 5(a) also shows that the highest instantaneous distillate production occurred when the height was 20 mm. With higher water levels in the basin, the distillate produced was less than 40 ml.

Figure 5(b) shows that the rate of distillation increases with decreasing volume of water in the still. The total volume of distillate of 202 ml, 163 ml and 130 ml were recorded at different levels of 20 mm, 40 mm and 60 mm respectively. The productivity of the solar still at h=20 mm was 674 ml/m^2-day (67.4 ml/m^{2}h). At h=40 mm, the solar still productivity was 542 ml/m^2-day (54.2 ml/m^{2}h) while it was 434 ml/m^2-day (43.4 ml/m^{2}h) at h=60 mm. The productivity is less than that reported by Ahsan et al. [20], Gomkali and Datta [3], Ighodalo and Ebhodaghe [7] and Naim [4]. However, it was observed that the volume of distilled water produced by the solar still varied inversely with the volume of water in the still basin. The likely reason for this is that the energy required to raise the temperature of the liquid, and hence the kinetic energy of the molecules, increased with the volume. Therefore, the solar still will perform better at a minimal water level which is sufficient to cover the entire basin surface area. This requires that an efficient feed water control valve is installed for proper regulation of the feed water.

Reed [21] estimated the minimum daily drinking water required for a person to be 3 to 4 litres per day. The productivity of the solar still is less than the minimum required quantity of water for survival. The use of sun tracking has been proposed by Taiwo [22] to increase the temperature and consequently improve the productivity of the solar still. Other methods proposed include preheating the feed water, reducing the temperature of the glass surface by using cooling water on the glass cover, using dye in the basing and using energy storing materials [9].

The efficiency of the solar still has been estimated for the different depths of water in the solar still. For a water depth of 20 mm, the efficiency was 29.1% while efficiencies of 23.3% and 18.7% respectively were obtained for water depths of 40 mm and 60 mm in the basin. It appears the level of water affects the thermal efficiency of the solar still. This is probably so because more energy was consumed in heating a larger quantity of water to increase its temperature. This implies that, apart from improving productivity of the solar still, the efficiency can also be improved by maintaining a minimal water level within the solar still by the use of an efficient water regulator.

The results from the tests from the laboratory which characterized the physical, chemical and microbiological properties of water before and after distillation in the still are presented in Tables 1 and 2. It was observed that conductivity reduced from 75 μS/cm to 47 μS/cm; total dissolved solids reduced from 50 mg/l to 32 mg/l; and the total hardness reduced significantly.

It was also observed that there was a reduction in the chemical and elemental constituents in the water after distillation in the water still. The total bacteria count also reduced. The values obtained during the analysis were within acceptable ranges for drinking water when compared to standards from NIS [23] shown in Table 3.

Table 1. Physical and chemical characteristics of water before and after distillation in the solar still

Parameter	Before distillation	After distillation
pH	7.01	7.00
Conductivity (μS/cm)	74.7	47.7
Total dissolved solids (mg/l)	50.2	31.6
Total suspended solids (mg/l)	Not detected	Not detected
Turbidity (FTU)	0.0	0.0
Total hardness (mg/l)	28.0	18.0
Total organic matter (mg/l)	Not detected	Not detected
Nitrate NO_3^- (mg/l)	0.41	0.22
Phosphate PO_4^{3-} (mg/l)	0.006	0.002
Sulphate SO_4^{2-} (mg/l)	3.0	2.0
Copper Cu (mg/l)	0.04	0.02
Iron Fe (mg/l)	0.07	0.03
Manganese Mn (mg/l)	0.02	Not detected
Lead Pb (mg/l)	Not detected	Not detected
Zinc Zn (mg/l)	0.47	0.25

Table 2. Microbiological characteristics of water before and after distillation in the solar still

Parameter	Before distillation	After distillation
Total coliforms	Nil	Nil
E. Coli	Nil	Nil
Virus	Nil	Nil
Total bacterial count	1.3×10^1	1.0×10^1

Table 3. Parameters and maximum allowable limits for drinking water [23]

Parameter	Maximum permitted value	Health Impact
pH	6.5-8.5	None
Conductivity (μS/cm)	1000	None
Total dissolved solids (mg/l)	500	None
Total suspended solids (mg/l)	N/A	N/A
Turbidity (FTU)	5	None
Total hardness (mg/l)	150	None
Total organic matter (mg/l)	5	Cancer
Nitrate NO_3^- (mg/l)	`0.2	Cyanosis and asphyxia (blue baby syndrome) in infants under 3 months
Phosphate PO_4^{3-} (mg/l)	N/A	N/A
Sulphate SO_4^{2-} (mg/l)	100	None
Copper Cu (mg/l)	1	Gastrointestinal disorder
Iron Fe (mg/l)	0.3	None
Manganese Mn (mg/l)	0.2	Consumer acceptability

Table 3 (continuing). Parameters and maximum allowable limits for drinking water [23]

Parameter	Maximum permitted value	Health Impact
Lead Pb (mg/l)	0.01	Cancer, interference with Vitamin D metabolism, affects mental development in infants, toxic to the central and peripheral nervous systems.
Zinc Zn (mg/l)	3	None
Total coliforms	10	Indication of faecal contamination
E. coli	0	Urinary tract infections, bacteraemia, meningitis, diarrhoea, acute renal failure and haemolytic anaemia
Virus	N/A	N/A
Total bacterial count	N/A	N/A

CONCLUSIONS

A simple laboratory scale solar water still with dimension 600 mm × 500 mm × 250 mm, capable of holding 75 litres of water, was developed and evaluated. The maximum temperature in the still occurred in the vapour region of the space between the water and the glass cover reaching up to 66°C, with the temperature of water in the still reaching up to 60°C. The productivity of the still varied with the level of water in the still. The productivity of the solar still with a water depth of 20 mm was 67.4 ml/m2h while productivities of 54.2 ml/m^{2}h and 43.4 ml/m^{2}h were obtained for water depths of 40 mm and 60 mm respectively. The efficiency of the solar still reached up to 29.1%.

Characterization of water before and after distillation in the solar still showed a reduction in chemical and microbiological constituents after distillation. It is recommended that the height of water in the solar still should be kept to a minimum but enough to cover the water still for best results. Further work will require concentrating on improving the productivity and efficiency of the solar water still. However, the solar still can be produced at a cheap cost and in small scale workshops for developing countries.

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