Contents list available at IJRED website

International Journal of Renewable Energy Development

Journal homepage: https://ijred.undip.ac.id

Research Article

Experimentation on enhancement of solar still performance

Sonia Z. Issaq, Shamil K. Talal, Aasim A. Azooz*

Department of Physics, Faculty of Science, Zakho University, Zakho - Kurdistan - Iraq

Abstract. This work presents new results from controlled experiments using well-designed and constructed single-inclination solar stills. The aim of these experiments is to explore methods for enhancing still performance by studying the individual effects of three types of methods. Specifically, the experiments investigate the actual effects of still basin water depth, the use of a sensible heat storage medium, and the treatment of the inner glass surface with waxy substances. The main distinction in this work is the use of solar stills that can achieve thermal efficiencies in excess of 40% under favourable weather conditions without any modification. This high efficiency level allows for meaningful analysis of the impact of modifications on still performance. The results indicate that still yield, productivity, and thermal efficiency decrease significantly when the water depth in the basin exceeds 6 cm. additionally, introducing black gravel in excess of a 2% gravel to water mass ratio in the still basin does not produce a significant change in still thermal efficiency. Treatment of the still inner glass surface with two types of waxy materials resulted in large drop in still performance.

Keywords: Desalination, Solar Still, Thermal Efficiency.

Received: 25th March 2023; Revised: 12th May 2023; Accepted: 23rd May 2023; Available online: 2nd June 2023

1. Introduction

The need for water desalination to obtain freshwater is becoming a more and more pressing issue over most parts of the globe. Among the several methods used for water desalination, solar still is considered as one of the methods of choice in many dry suburban regions. This is due to its low construction cost, ease of assembly, quiet operation, and practically zero running costs. Consequently, the solar still has been the subject of many theoretical and experimental research studies worldwide. Most of these studies are mainly directed towards establishing the best ways and design modifications aimed at increasing the still water productivity and thermal efficiency. Such modifications covered almost all parts of the still structural elements and operating parameters. Most modifications are mainly concerned with improving one or more of the main three thermal processes taking place within the solar still. These processes are: (1) Energy absorption and evaporation of the water within the still basin, (2) Condensation of the evaporated water on the glass cover, (3) The down slide flow of the condensed vapour (water drops) along the glass cover. Improving this latter process inherently includes minimizing the process of re-vaporization of water drops from the glass cover surface.

In spite of the large number of solar still performance enhancement techniques described in literature, those associated with low cost, and simplicity are considered more favourable. Three such favourable techniques are: operating the still at the optimum basin water depth, adding some sensible heat storage material in the still basin, and changing the physical or geometrical properties of the glass cover.

Tiwari and Tiwari (2006), carried out model analysis and experimental measurements of the effect of water depths between 4 and 18 cm on heat and mass transfer in a passive solar still under summer climatic conditions. Their results show general decrease of still efficiency with increasing water depth. However, it may be worth pointing out that the measured highest still overall efficiency at water depth of 4 cm was only 18.94%. Tarawneh (2007) measurements have shown that the yield of uncooled glass still productivity was highest when water depth was 0.5 cm. In a study by Phadatare and Verma (2007) using plastic covered, it was reported that daily distilled water yield did not change much for water depths between 4 – 12 cm, with only slightly higher yield at 2 cm. The instantaneous thermal efficiency on the other hand showed systematic increase from about 10% at water depth of 2 cm to about 35% at 12 cm. Khalifa and Hamood (2009) measured productivity decrease of up 48% when the still water depth is increased from 1 to 10 cm. Jamal and Siddiqui (2012) studied double slope still performance at 2, 3, 4, and 5 cm water depths, concluding that performance decreases with increasing water depth Taghvaei *et al* (2014), concluded that increasing water depth will result in increased still thermal efficiency and productivity when measurements are carried out over several days. Thakur and Pathak (2017) reported that solar still productivity was higher when water depth was 1 cm compared to those at 2 and 3 cm. Mohamed *et al* (2019) showed that using water depth of 0.5 cm results in better productivity compared to 1, 2, 3, and 4 cm. Kumar *et al* (2020) concluded that increasing basin water depth from 3 cm to 9 cm resulted in a decrease in efficiency from 45.11 to 36.7% for a still coupled with heat solar collector. Naveenkumar *et al* (2022) reported that the optimum water

---

* Corresponding author
Email: aasimazooz1@yahoo.com (A.A.Azooz)

https://doi.org/10.14710/ijred.2023.53239

depth in a conventional still is 3 cm. Khafaji *et al* (2022) measurements indicate that water depths of 1 cm result in better performance compared to 2 and 3 cm. Singh *et al* (2022) reported that water depth of 4 cm produced more yield compared to 5, 6, and 7 cm.

Another method used to increase absorption of solar radiation within the water basin is through the use of materials with specific heats lower than that of water. The temperature of such materials will rise quickly causing faster increase in surrounding water temperature. This will result in enhanced evaporation. These materials are called sensible heat storage materials (SHS). Sakthivel and Shanmugasundaram (2008), argued that the use of gravel resulted in a 17 – 20% increase in yield. El-Sebaii *et al* (2009) measurements suggest that the use of 10 kg of sand as SHS material in the basin resulted in an increase in efficiency from 27% to 37.8%. Black granite gravel was used by El-Sheikh (2016), measured daily yields of 2181 ml and 1802 ml for stills with and without granite gravel respectively. Yield values with and without gravel reported by Jadhav (2011), are 3.784 L/m^2.day and 2.358 L/m^2.day. Shanmugan *et al* (2012) tested marble stones, pebbles, black stones, calcium stones, and iron scraps. Calcium stones were found to result in the best performance. Sandstone and marble were used by Panchal *et al* (2015, 2018), produced about 3900 and 3450 mL/m^2.day compared to about 3000 ml/m^2.day by conventional still. Graphite was used by Kabeel *et al* (2018), resulted in exceedingly high accumulated production of 7.123 L/m^2. Day, 7.475 L/m^2 day, 7.937 L/m^2. day, 8.249 L/m^2. day, and 8.52 l/m^2.day using paraffin wax with 0.0%, 5%, 10%, 15%, and 20% graphite nanoparticles mass concentrations respectively, compared to only 4.38 l/m^2.day. Balaji *et al* (2019) reported that yields of stills using Basalt, Pebbles, Sandstone, Granite, and Blue metal stone were 2554, 2076, 2405,1477, 2406 ml/m^2.day compared to 2029 mL/m^2.day for conventional still. In summary, the claimed outcomes of such techniques suggest increases in thermal efficiency of between 10 – 80%.

Glass wettetabity effects studies go back more than half a century ago. Bahadori and Edlin (1973) reported that treatment of still glass glazing with either sodium metasilicate or hydrofluoric acid reduces increases water production. There have been several more recent studies related to changing glass wettetabity effects. Begum *et al* (2016) reported that still yield is reduced significantly when the glass cover is replaced by PVC sheet. Baticados *et al* (2020), applied both oxygen plasma treatment and graphine surface enhancement to the inside glass cover surfaces and the metal absorber plates. Peng *et al* (2021) measured 70% increase in still yield when the glass cover is treated with commercial anti-fogging agents. Thakur *et al* (2021) used nano-materials to assist in producing the better down slide of water droplets. This resulted in 15.6% increase in distilled water yield.

It is worth mentioning that some of the above three techniques used to enhance solar still performance have been mentioned in several review works on solar stills which appeared in literature during the last decade. These include Muftah *et al* (2014), Manchanda and Kumar (2015), Kalita *et al* (2016), Ithape *et al* (2017), Essa *et al* (2022), Ayoobi and Ramezanizadeh (2022) and Younis *et al* (2022)

Results reported about increases in still performance metrics using one of the above three particular designs show wide variations. Increases in still efficiencies in the range of 10 - 300% have been reported in some cases. Reported baseline efficiencies for simple unmodified stills working under similar conditions, range from 10 to 40%. A compilation of average output of standard simple solar stills from ten references presented by Ayoub and Malaeb (2012), showed scattering of daily yields ranging between 0.98 and 4.15 (L/m^2.day), with mean and standard deviation of 2.5 and 1.1 (L/m^2.day) respectively. These wide variations in daily yields and thermal efficiency may be due to two main factors. The first is the large variation in other weather parameters, even when daily solar radiation is the same. The second can be attributed to differences in still construction caused by materials, thermal insulation, type of glass, and other factors.

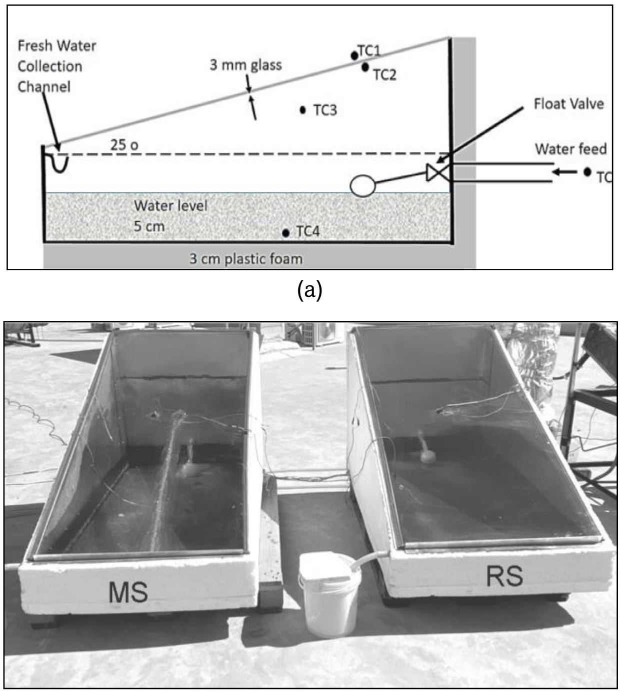
Furthermore, Taghvaei *et al* (2014) raised a point concerning their conclusion that still performance results obtained from several days of runs can be drastically different from those obtained from one-day runs. Consequently, one can argue that there is a reasonable case for carrying out measurements over several days to make a more solid conclusion concerning the effect of a particular structural or operational modification on solar still performance.

Within this context, the aim of this work is to present experimental results on the effects of still basin water depth, the use of gravel as sensible heat storage medium (SHS), and the still glass treatment with waxy materials on the performance of a solar still. The results presented are based on repeated measurements for at least three days under each experimental condition and are to be compared with corresponding published results. High care was taken to ensure that the baseline still efficiency is as high as possible. Measured baseline efficiencies were in excess of 40% on some days. Such thermal efficiencies were achieved as a result of efforts spent to ensure maximum possible thermal insulation and highest sunlight absorption.

2. Experimental Setup

Two identical solar stills were constructed. The first is called the reference still (RS), while the second is called the modified still (MS). Each still consists of a rectangular basin area of $1.33 \times 0.75 = 1.0$ m^2, and 12.5 cm. in depth. The stills are made from 2 mm thick Aluminium sheets. The inclination angle of the 4 mm thick glass cover is 25°. The glass cover sits tight on the folded rims of the basin using silicon rubber seals. Good thermal insulation of the stills from the sides and the bottom is provided by 5 cm thick plastic foam. The inside of each still basin was painted with Alkyl type spray black paint. The selection of this paint was based on the results of a simple exploratory experiment during which seven types of organic and inorganic based were used to paint seven small steel dishes. The dishes were filled with 500 mL of water each and exposed to the sunlight together with an eighth similar, but unpainted dish for the daytime period. The water temperature in each dish was measured every hour. The water in the steel dish painted with Alkyl type spray black paint registered higher temperatures compared to other paints throughout the day. It was thus selected as the favourite one to use.

Water level within the basins was controlled using floating ball valves. Water condensed on the inner glass surface is collected via a horizontal channel into a plastic container. Feed water temperature, basin water temperature, inner and outer surfaces glass cover temperatures, vapour temperature, and atmospheric temperature are recorded every five minutes using K-type (Nickel-Chromium/Nickel-Alumel) thermocouples with a sensitivity of 41 μV/°C each. The accuracy of these thermocouples is ±2.2 ° C [ROTEMP instruments]. The set of these thermocouples are connected to an Arduino Mega 2560 R3electronic data acquisition system (Arduino 2011), which logs acquired data to the PC via SSD card or through *thingspeak.com* cloud website Unfortunately, and in spite of experimenting with several types of adhesives, the two thermocouples attached to the inner glass surfaces in both stills kept falling many times because of temperature and humidity. Consequently, inner glass temperatures are lacking most of the time. The schematic



(a)

(b)

Fig 1. Experimental Setup (a) Schematic diagram of solar still. (b) RS and MS solar stills.

diagram of the still is shown in Figure 1. Weather parameters including temperatures, relative humidity, and wind speed are recorded every five minutes using a Nexus wireless Weather station (Optics-Pro) positioned beside the solar still. Furthermore, all hour-by-hour weather parameters including temperatures, wind speed, relative humidity, and dew point are obtained from Zakho Meteorological Station. The two sets of weather data were compared to each other. No differences exceeding 1% were recorded. The minuet-by-minuet solar irradiation and total daily solar energy data were measured using cosine corrected solar radiation meter PCE - SPM1 [PCE instruments]. The instrument has a computer logging system. The experiment data flow chart is shown in Figure 2.

The distilled water is collected using a 10 - litre plastic container. To account for any water loss due to evaporation from the container, the water loss from an identical container containing some water is measured over the same period. The collected distilled water quantities are measured using a digital weight-measuring device with a sensitivity of ±1 gm. The water quantity evaporated from the second container is added as a correction to the water quantity produced by the solar still. Three sets of independent experiments were carried out. These involved the study of effects of water depth in the still basin, the presence of different quantities of gravel with the water in the basin and the treatment of the still inner glass surface with two types of hydrophobic materials.

2.1. The water depth experiment

The RS was operated at a constant basin [illegible]ter depth of 5 cm throughout this experiment. The MS was used as a modified still, and its performance for each water depth was compared with that of the RS when both stills were operated on the same day. Water depths of 2, 2.5, 3, 3.5, 4, 5, 6, 7, 8, and 9 cm were used in the MS, in addition to the 5 cm depth used in the RS during the water depth experiments.

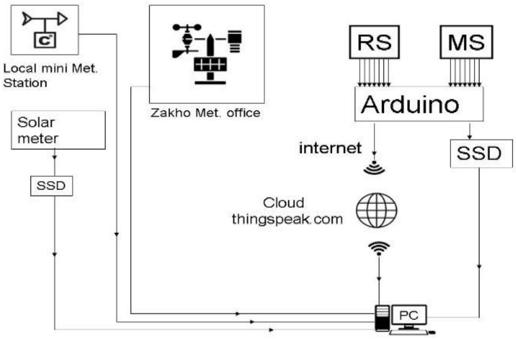


Fig 2. Data flow diagram

2.2. The Gravel Experiment

Quantities of gravel of 500, 1000, 1500, 2000, 2500, 3000, 3500, 4000 and 4500 gm were added in the MS basin during the gravel effect experiment, while keeping the water level in both stills at 5 cm.

2.3. The Glass Treatment Experiment

In this experiment, the glass cover of the MS was treated separately with two types of commercially available waxy materials. The first is WiNSO Professional Quick Wax WiNSO. (n.d.). The second is Gardx Protection Conserver GardX. (n.d.). Both products are hydrophobic products, with high water repellent ability, used as cars body drying agents.

Figure 3 summarises the setup configurations of the two stills used during the three experiments described above. Freshwater outputs were measured daily during several periods: July 10-21, August 21-26, September 1-30, October 1-15, October 26-30, November 7-9, and November 13-15. Weather parameters were also recorded during these periods. Multiple measurements of freshwater yield were taken during these periods, with at least three measurements for the different MS water depths, independently at each gravel quantity added to the still basin and glass inner surface treatment. The plotted values and error bars for yields, productivity, and thermal efficiency represent the averages and statistical standard errors of these repeated measurements. The values and error bars for the RS are the averages and statistical standard errors for measurements made

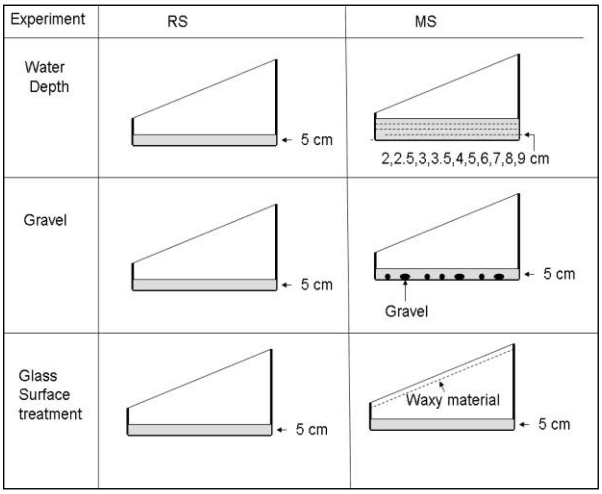


Fig 3 Experimental configurations during the three experiments

on the same days as the corresponding MS measurements. The daily thermal efficiency (*E*) is calculated using the daily water yield (*M*), the daily solar radiation (*S*), and the latent heat of vaporization (*L*) at water temperature (*T₀*) using the relation given by Tiwari & Tiwari (2006)

$$E = \frac{\text{Output Energy}}{\text{Input Energy}} = M \times L/S \qquad (1)$$

$$L = 2.4935 \times (1 - 9.4779T_0 + 0.13132T_0^2 - 4.7974 \times 10^{-3}T_0^3) \qquad (2)$$

3. Results and Discussion

3.1. General trends

The performance metrics for a still exposed to a total daily solar radiation energy (S) are the daily yield (M), the daily productivity (P), and the daily thermal efficiency (E). The latter two quantities are important because they represent more instructive performance metrics compared to daily yield. The productivity (P = M/S) defined as the yield per unit solar radiation energy, eliminate to some degree the effect of solar energy on the yield. Thermal efficiency is even more instructive because it eliminates the effects of both solar radiation and still feed water temperature (T_0).

Figure 4 shows plots of all three-performance metrics for the RS data acquired throughout the experiment against both daily solar radiation and ambient temperature. It is clear that while Figure 4a shows a strong dependence of daily yield on daily solar radiation. This dependence is in good agreement with a second-degree polynomial correlation function proposed by Khalifa, and Hamood (2009).

$M = 0.0036 \times S^2 + 0.0701 \times S + 0.2475 \quad R^2 = 0.762$ M in Liter, and S in MJ. (3-a)

$M = 46.656 \times S^2 + 252.360 \times S + 247.500$ M in mL, and S in kWh. (3-b)

They derived this correlation function from fitting a compilation of 180 data points measurements for the relation between yield and solar radiation from eight references, Cooper (1973), Garg and Mann (1976), Tanaka, Yamashita & Watanabe(1982), Ahmed (1988), Zaki, Fatani & Al-Turki (1992), Zaki, El-Dali, & El-Shafiey (1992), Zein & Al-Dallah (1993) and Tahir (1997). This equation is further used to calculate the productivity and thermal efficiency. Results of the calculations are plotted together with the data in Fig 4b and 4c, respectively. Good agreement of our experimental data with equation 3b prediction is observed again. It is worth mentioning that dependence of productivity and thermal efficiency on solar radiation in Fig 4b & 4c, is weaker than that of the yield. The data indicate that the average increase in daily fresh water yield changes by about 22% for an increase in daily solar radiation of 1 kWh/m². The corresponding changes in productivity and thermal efficiency, amount to only about 5%. Furthermore, the figure demonstrates clearly the large fluctuations in all metrics even for close solar radiation values. Minimum and maximum thermal efficiency values registered are 34.8 and 48.4% within the narrow solar energy range of 6.23 and 6.30 kWh/m². Such fluctuations are reflections of effects of other weather conditions such as temperature, humidity, etc.

The most important weather parameter which affects still performance besides solar radiation is the atmospheric temperature. To demonstrate this effect the three metrics are plotted against ambient temperature in Figure 4d, e, & f. It is clear here that high still performance is associated with large ambient temperatures and vice versa. This effect is reflected in all following results for water depth, gravel, and still glass treatment data presented below. Higher RS and MS metrics are common in the water depth experiment which was carried out during the hotter months of July, August and September. These metrics were lower in the gravel experiment which took place mainly during the first half of October. The lowest metrics are obtained in the glass treatment experiment which took place during the cooler period in late October and November. The

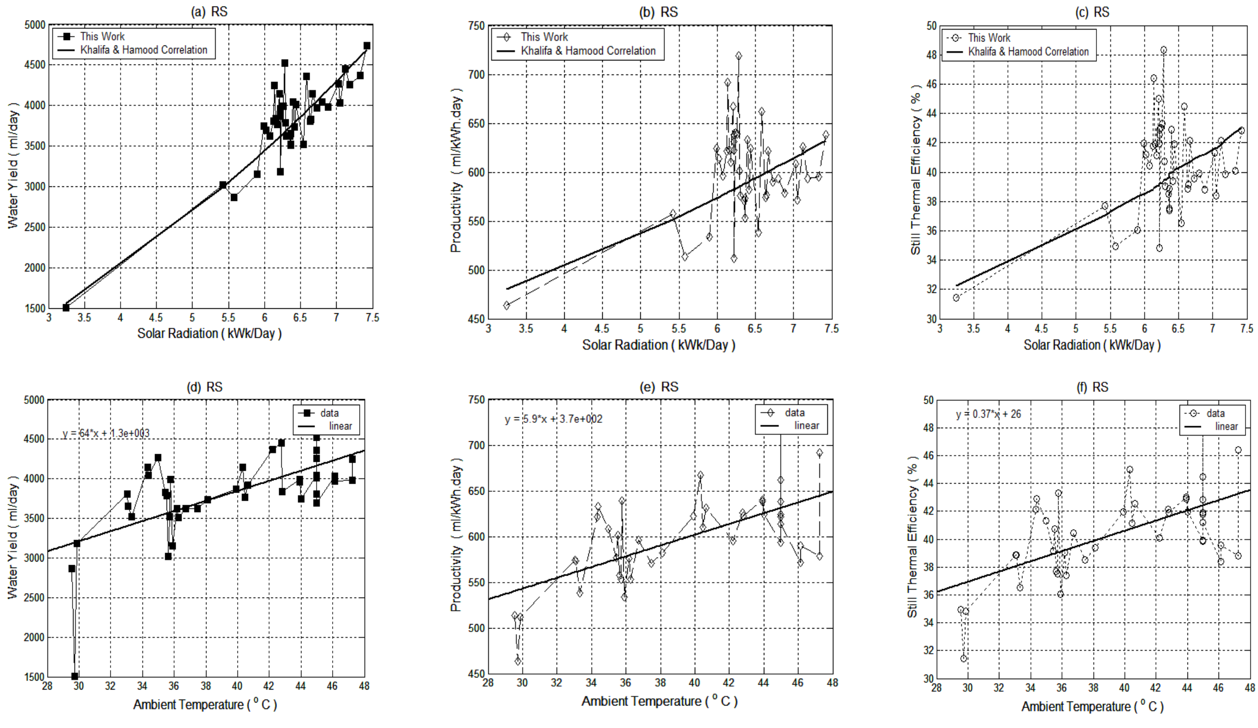


Fig 4 The three solar still performance metrics for RS solar still (water depth = 5 cm.), plotted against daily solar radiation and ambient temperatures. (a &d) Daily freshwater yield, (b & e) productivity, (c & f) thermal efficiency.

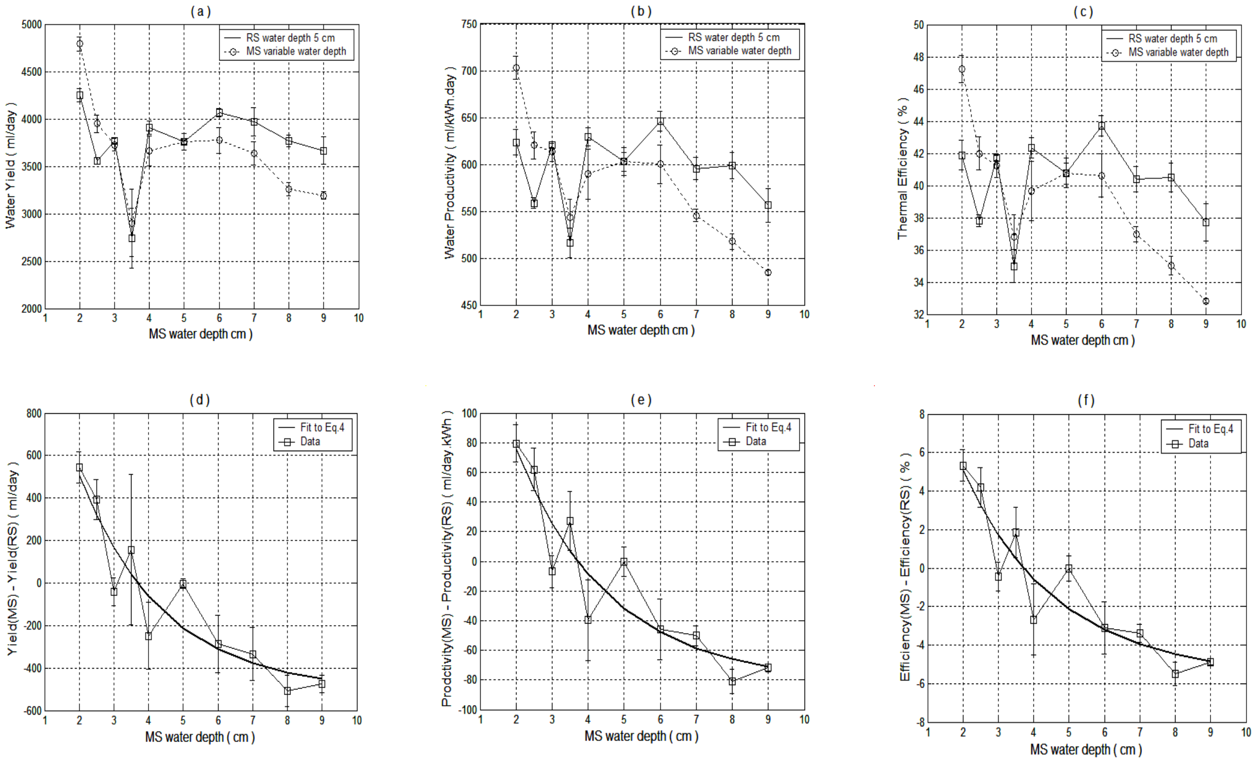


Fig 5. Comparisons between the RS and MS performance metrics against (a) daily yield, (b) productivity, and (c) thermal efficiency, as functions of water depth. (d), (e), and (f) differences between MS and RS yield, productivity, and efficiency respectively, fitted to equation (4)

temperature dependence data are well described by linear fits shown in the figures.

3.2. Water Depth Experiment

Solar still performance measurements for different MS basin water levels were carried out for basin water depths of 2, 2.5, 3, 3.5, 4, 5, 6, 7, 8, and 9 cm. Measurements at each water depth were repeated minimum three times. Figure 5 displays the yield, productivity, and thermal efficiency of both RS and MS, plotted against the water depth in the MS. The water depth in the RS was kept constant at 5 cm. Each point on the graph represents the mean of at least three measurements made on three different days. The error bars on the graph indicates the standard errors. For the RS, the points are averages of measurements taken on the same days as the corresponding MS points. The significant drop in all three metrics at a water depth of 3.5 cm was caused by the unstable, dusty, and windy weather in the Zakho area between September 20th and September 24th, 2022, when the measurements at that water depth were taken, Meteoblue, (2022, September). Nevertheless, this data is included for completeness purposes. Despite the observed fluctuations, all three performance metric values are higher for MS at water depths less than 4 cm and they are approximately equal at water depths of 4 - 5 cm, error bars. Furthermore, the results indicate a systematic decrease in all three metric values for water depths above 5 cm. The MS recorded the highest average yield of 4820 mL at a water depth of 2 cm compared to 4280 mL for the RS over the same measurement days. These values correspond to efficiencies of 47.6% and 42.2%, respectively. To clarify things further, the differences between corresponding metrics of both stills (MS-RS) are plotted in Figs 5d, e, & f. These differences show systematic decrease with increasing water depth. The three sets of data are fitted to the empirical equation

$$y = a_1 e^{a_2(x-a_3)} - a_4 \tag{4}$$

with *x* representing the water depth, and y representing one of the still metrics and $a_1 \ldots a_4$ are free fitting parameters to be determined by the program.

Fits with over 95% confidence level were obtained for each of the three metrics as shown as solid lines. The values of the

Table 1
Fitting parameters to equation (4) for the three still metrics

Still Metric	a_1	a_2	a_3	a_4
Yield (mL/Day)	99.9947	0.4098	7.6641	510.1974
Productivity (ml/Day.kWh)	12.4344	0.3826	8.6346	81.8447
Efficiency (%)	5.1526	0.3777	3.9254	5.5780

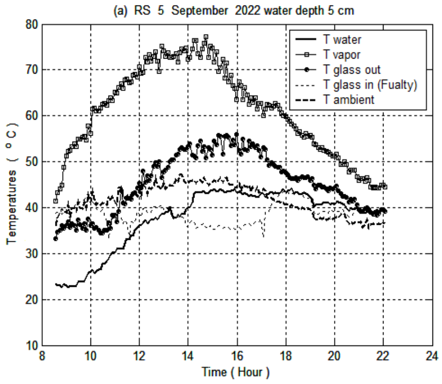
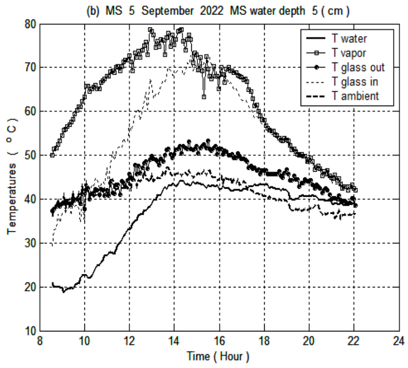


Fig 6 Temperatures measured as functions of time for the two stills working at the same basin water depth of 5 cm. (a) RS, (b) MS.



fitting parameters obtained are presented in Table 1. The data shows decreasing performance with increasing water depth. This result is in agreement with most published works on water depth effects. Although our measurements are carried out over several days' spans as recommended by Taghvaei *et al* (2014), the results did not show the reverse increase in efficiency with increasing water depth reported in the latter reference.

Figure 6a & 6b shows the temperatures at different positions in the two stills when both are working at the same water depth of 5 cm. Apart from the faulty fallen thermocouple which measures the inside of the glass cover temperature in the RS, other corresponding temperatures in the two stills are approximately all equal within the standard accuracies of ±2.2 ° C of the thermocouples used. This comparison of the two sets of temperatures serves to ensure that the two stills are almost identical in both structure and operation. Figure 7 displays the basin water temperatures on plots (a, b, c, & d) on the left side of the figure, and the vapor region temperatures on plots (e, f, g, & h) on the right side for RS and MS, at water depths of 3, 4, 7, and 9 cm. The figure illustrates the consistent changes in these temperatures as the water depth varies. By analyzing this figure, along with similar plots at other water depths not shown here, one can infer that the daily operation of the solar still involves three distinct stages.

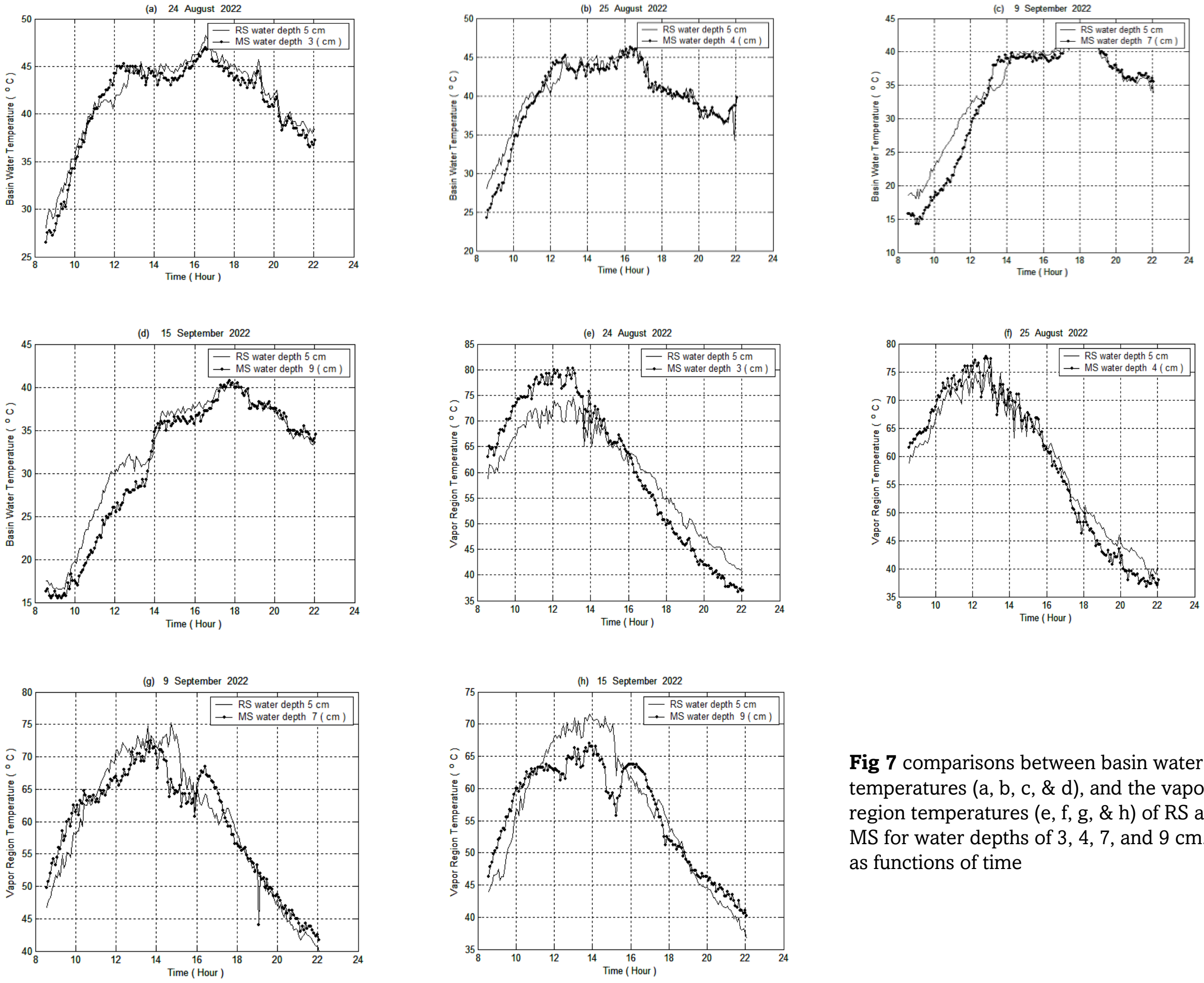


Fig 7 comparisons between basin water temperatures (a, b, c, & d), and the vapour region temperatures (e, f, g, & h) of RS and MS for water depths of 3, 4, 7, and 9 cm. as functions of time

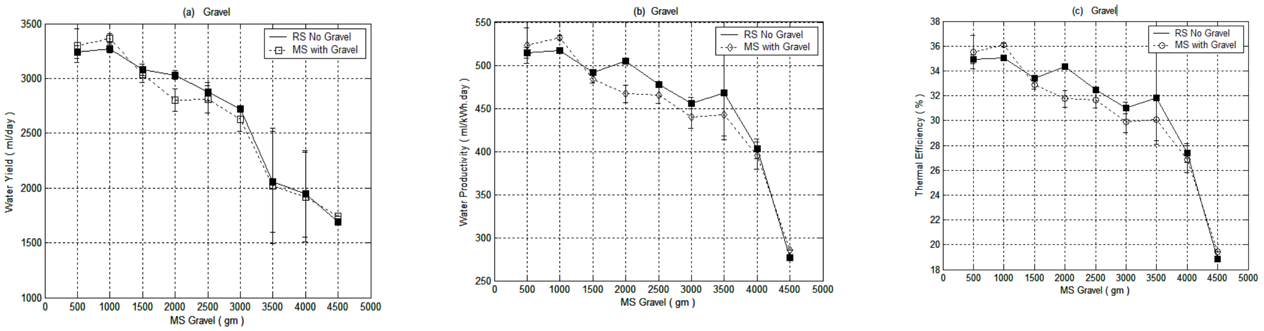


Fig 8 Comparisons between the RS and MS performance metrics (a) daily yield, (b) productivity, and (c) thermal efficiency against the amounts of gravel in the MS basin

The first stage is the transient stage, which lasts from 8 AM until around 12-14 PM when the thermal equilibrium of the water with the surroundings is reached. During this stage, the water temperature increases rapidly. The primary difference between the water temperatures in the two stills is noticeable at this stage. For water depths below 5 cm in the MS, the water temperatures are almost equal -within the accuracy of the sensors- to the corresponding ones in the RS. However, as the water depth in the MS becomes greater than that in the RS, the MS temperatures become significantly lower than those in the RS. This can be attributed to the fact that a larger quantity of water in the basin requires more time to warm up. The duration of this stage depends on various weather parameters. The second stage is the thermal equilibrium stage, which begins at the end of the first stage and continues until sunset. During this stage, the water temperatures of the two stills are almost identical for all MS water depths. The third stage is the cooling-down stage, which spans the period after sunset. During this stage, the water temperature decreases. For water depths below 5 cm, the MS exhibits systematically lower temperatures than the RS. However, for water depths greater than 5 cm, the situation reverses. This is due to the heat capacity differences between the two stills.

The three stages are further highlighted in the vapor region temperature plots (Fig 7e, f, g, & h). For water depths below 5 cm, the MS vapor region temperature is higher than that of the RS throughout both the warming-up and thermal equilibrium stages. However, for water depths greater than 5 cm, a turnover occurs at the transition point from the first to the second stage. The MS vapor temperatures become significantly lower than those in the RS, and the difference between the two increases with increasing water depth. As for the cooling-down stage, it appears that the MS vapor region maintains lower temperatures than the RS when the water depth is less than 5 cm. The opposite occurs for water depths greater than 5 cm.

The MS achieves increased efficiency at water depths less than 5 cm in Figure 5 because it contains less water and, therefore, has a lower heat capacity. This causes the MS to reach the thermal equilibrium stage faster than the RS, as evidenced in Figure 7-a & b. Although both stills reach equal temperatures at the end of the warming-up stage, the MS water remains at this temperature for a longer period, resulting in more vaporization. This is also reflected in the higher vapor temperatures shown in Figure 7-e & f.

However, for water depths larger than 5 cm, the situation is reversed, and the RS water temperature is systematically higher than that of the MS due to the latter's larger heat capacity. This results in less evaporation and reduced yield and thermal efficiency, as seen in the lower vapor temperatures in the MS compared to the RS in Figure 7-g & h. It's worth mentioning that the small changes in the rates of temperature increases in Figures 7-a to d may be due to the initiation of convection currents caused by the temperature gradient between the bottom of the basin and the water surface. These changes are less evident in the MS when operating at small water depths because the shallow water results in a more uniform temperature distribution through heat conduction rather than convection.

3.3. Gravel Experiment

Figure 8 shows the comparisons between the three still performance metrics when amounts of gravel are added to the MS basin. The water depth in both basins is kept constant at 5 cm. The figure shows that all three metrics values for the MS are slightly lower than the corresponding values for the RS apart from the cases when the gravel quantity was less than 1000 gm. This suggests that adding gravel to the solar still has no positive effect on still performance in spite of the fact that the gravel presence can result in changes in basin water and vapour region temperatures as can be observed in Figure 9. It is evident from Figure 9 that gravel quantities can affect temperatures developments within the basin water (a, b, c, & d), and the vapour region (e, f, g, & h). For small amounts of gravel, the MS temperatures assume values lower than the corresponding ones in the RS at the beginning of the warm-up stage but with a faster rate of increase. The MS water temperature also shows no convection currents related change in its fast rate of increase. The observed faster rate of temperature increase is the result of the smaller heat capacity of the gravel. This caused the MS water temperature to exceed those in the RS and reaches the thermal equilibrium stage sooner. Furthermore, the presence of gravel in the MS will increase conduction heat transfer due to the higher thermal conductivity of gravel. As the amount of gravel is increased, the gravel will cover larger parts of the painted still bottom. This is equivalent to replacing the painted bottom with the gravel. The water temperatures in the two stills will become much similar as shown in Figure 9 – c &d. These effects are also reflected in the vapour temperature plots.

The effect of gravel on the MS vapour region temperature is shown in Figure 9 – e, f, g, and h. Small amounts of gravel in the MS seem to cause this temperature to become significantly higher than the corresponding ones in RS during the warming up and equilibrium stages. However, the difference between the temperatures of the two still tend to show a slight decrease with further increases in the gravel quantity as can be observed from the Figure 9 – g & h. The situation is different in the cooling-down region where the small amounts of gravel act to reduce the cooling-down temperatures in this region. However, further increases in the gravel quantities cause the two stills to have almost equal temperatures in this region. The observed

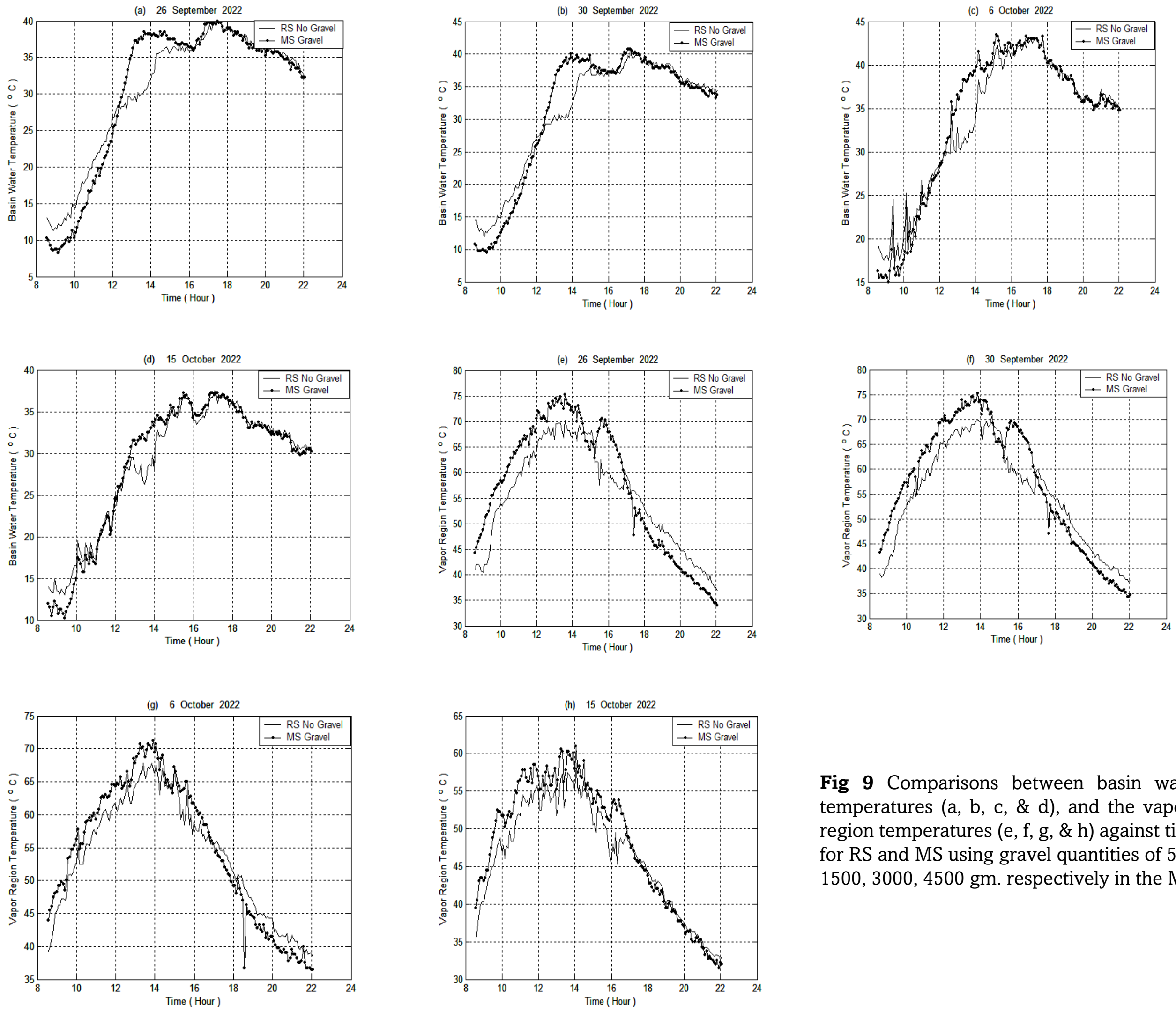


Fig 9 Comparisons between basin water temperatures (a, b, c, & d), and the vapour region temperatures (e, f, g, & h) against time for RS and MS using gravel quantities of 500, 1500, 3000, 4500 gm. respectively in the MS.

temperature patterns are due to two main reasons. The first is the higher specific heat of the gravel. The second is the reduced absorbance of light by the gravel compared to the black paint used. The two effects produce opposed effects. While the use of small amounts of gravel may result in a faster increase in water temperature, during the warming-up period, which results in some increase in evaporation, and vapour temperatures, the same effect will cause faster cooling of the vapour region during the cooling-down stage. The net effect is slightly more heating. This is reflected in the slightly higher performance metrics of the MS with small amounts of gravel. As the gravel is increased, the second effect becomes more dominant. Although the gravel is capable of reaching higher temperatures, the net absorbed energy will be less. Larger quantities of gravel will completely prevent sunlight from reaching the black painted basin bottom on one hand and produce faster cooling of the vapour during the third stage. This faster cooling will start even during the equilibrium stage. The net result is that the two effects will break even with no significant change in still performance metrics.

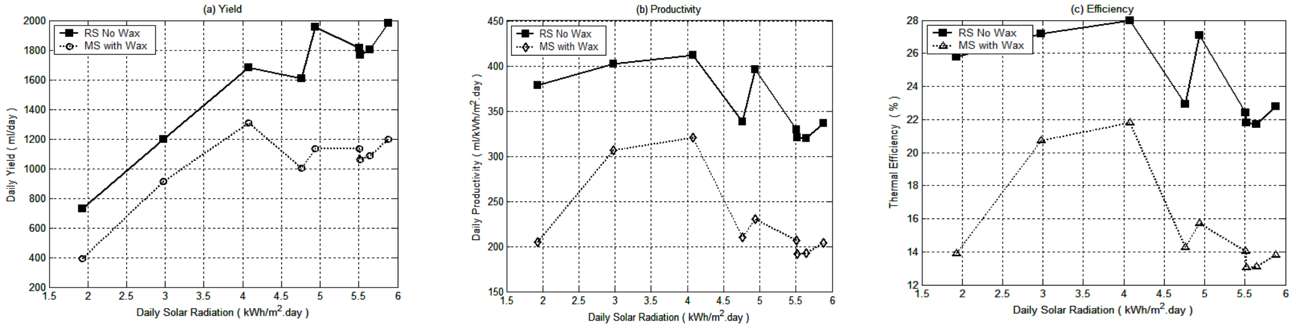


Fig 10 Effect of the Water repelling agent *Quick Wax* in MS solar still performance metrics (a) Yield, (b) Productivity, and (c) Thermal efficiency against total daily solar radiation compared to those RS.

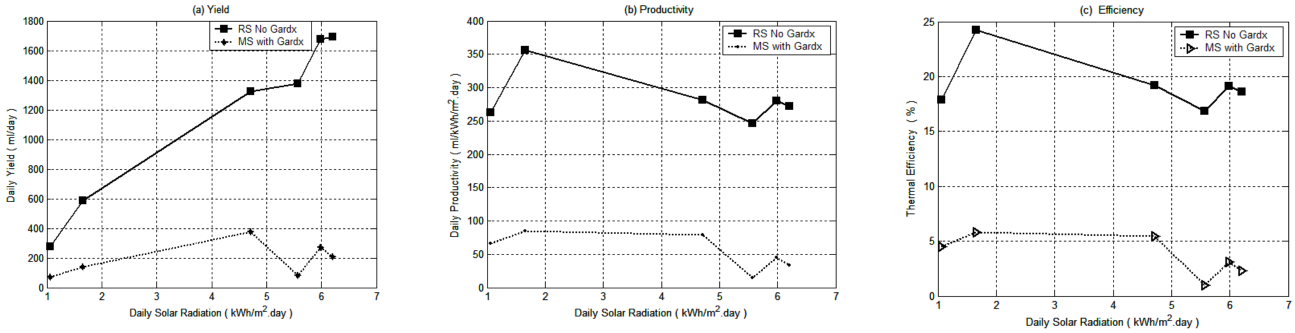


Fig 11 Effect of the Water repelling agent *Gardx* in MS solar still performance metrics (a) Yield, (b) Productivity, and (c) Thermal efficiency against total daily solar radiation compared to those RS

3.4. Inner Glass Surface Treatment Experiment

The purpose of this experiment was to investigate the effect of changing the water to glass adhesion properties on the solar still performance. Two types of commercially available materials were used for this purpose. The first is WiNSO Professional Quick Wax WiNSO (n.d). The second is Gardx Protection Conserver GardX (n.d)). Both products are hydrophobic cars body drying agents with high water repellent ability. The MS inner glass surface was treated with each of the two agents separately.

Figures 10 and 11 demonstrate the impact of Quick Wax and Gardx Protection agents on the RS and MS performance metrics with varying levels of daily solar radiation when applied to the inner glass surface of the still. Both materials are considered as hydrophobic agents. The results indicate a significant decrease in performance for both materials. Specifically, the application of Quick Wax resulted in an average MS thermal efficiency drop from 24.4% to 15.6%, while the effect of Gardx was even more pronounced, causing the average efficiency to drop from 19.3% to only 3.7%. These results are in clear contrast with those of Thakur *et al* (2021) where the use of nano-silicon spray, which is also has hydrophobic properties, is reported to results in an increase of 15.6% in efficiency. This is thought to be caused by the decrease in adhesion angle. However, this action seems to have been coupled with a negative effect that caused the droplets to fall back into the basin before reaching the collection channel.

4. **Conclusions**

The results of the study suggest that selecting high-quality paint and carefully insulating and sealing the solar still can lead to daily freshwater yields and thermal efficiencies of over 4000 ml/day and 40%, respectively, under favourable weather conditions. However, weather conditions, particularly ambient temperature, can have a significant impact on the still's performance. To obtain accurate performance measurements, it is necessary to measure the still's performance over several days or specify the full weather parameters for a specific day. The study confirms that passive solar stills perform better with shallower basin water depths, but an upper limit of 6 cm of water depth is suggested for the still to operate without significantly reduced performance. While small amounts of black gravel can result in a slight increase in still performance metrics, further improvements are not observed beyond a gravel-to-water mass ratio of 2%. The presence of hydrophobic materials on the inner glass surface can have a significant negative effect on the still's performance. Therefore, it is essential to take special care to ensure that the inner glass surface is free from any oily or waxy materials.

Ethical Approval

All authors declare that the work comply with all ethics related to scientific procedures and actions.

Consent to Participate

All authors have read the final draft of the manuscript and agreed to its contents.

Consent to Publish

All authors have given their permissions to publish this work and have authorized the corresponding author (Aasim Azooz) to carry out the necessary actions in this respect

Funding

All authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests

All authors have no relevant financial or non-financial interests to disclose.

Availability of data and materials

All data, material and software are available from the corresponding author on request.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Sonia Issaq, Shamil Talal and Aasim Azooz. The first draft of the manuscript was written by Aasim Azooz and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript

References

Ahmed, S. T. (1988). Performance of a single slope solar still with natural and forced modes of condensation. *Solar & Wind Technology*, 5, 637–643. https://doi.org/10.1016/0741-983x(88)90045-5

Arduino. (2011). Arduino Mega 2560 Rev3. Retrieved from https://store.arduino.cc/usa/mega-2560-r3

Ayoobi, A., & Ramezanizadeh, M. (2022). A Detailed Review Investigating the Mathematical Modelling of Solar Stills. *Frontiers in Energy Research*, 10, 879591. https://doi.org/10.3389/fenrg.2022.879591

Ayoub G. M. and Malaeb L. (2012). Developments in Solar Still Desalination Systems: A Critical Review. *Critical Reviews in Environmental Science and Technology*, 42:2078–2112. https://doi.org/10.1080/10643389.2011.574104

Balaji, R., Aravindh, V., Baburangan, J., Koushik, S., & Mahendran, P. (2019). Performance analysis of single slope solar still using sensible heat storage material. *Applied Innovations in Research*, 1(June), 120–127. https://doi.org/10.1007/s42621-019-0005-6

Bahadori, M. N., & Edlin, F. E. (1973). Improvement of Solar Stills by Surface Treatment of the Glass. *Solar Energy*, 14, 339-352. https://doi.org/10.1016/0038-092X(73)90091-1

Baticados, E. J. N., Capareda, S. C., Liu, S., & Akbulut, M. (2020). Advanced Solar Still Development: Improving Distilled Water Recovery and Purity via Graphene-Enhanced Surface Modifiers. *Frontiers in Environmental Science*, 8, 531049. https://doi.org/10.3389/fenvs.2020.531049

Begum, H. A., Abu-Yousuf, M., & Rabbani, K. S. (2016). Effect of top cover material on productivity of solar distillation unit. *Bangladesh Journal of Medical Physics*, 9. https://doi.org/10.3329/bjmp.v9i1.26944

Cooper, P. I. (1973). Solar distillation: The water crisis solution. *Solar Energy*, 15, 205–217. https://doi.org/10.1016/0038-092x(73)90033-8

El-Sebaii, A. A., Yaghmour, S. J., Al-Hazmi, F. S., Faidah, A. S., Al-Marzouki, F. M., & Al-Ghamdi, A. A. (2009). Active single basin solar still with a sensible storage medium. *Desalination*, 249(2), 699–706. https://doi.org/10.1016/j.desal.2009.06.071

El-Sheikh, I. H. (2016). Effect of Black Granite on the Performance on Single Slope Solar Still. *Misr J. Ag. Eng*., 33(1), 283–296. https://doi.org/10.21608/mjae.2016.30960

Essa, F. A., Abdullah, A., Majdi, H. S., Basem, A., Dhahad, H. A., Omara, Z. M., Mohammed, S. A., Alawee, W. H., Al-Ezzi, A., & Yusaf, T. (2022). Parameters Affecting the Efficiency of Solar Stills—Recent Review. *Sustainability*, 14(17), 10668. https://doi.org/10.3390/su141710668

GardX. (No date) GardX Protection Conserver [Product safety data sheet]. Retrieved April 29, 2023, from https://www.gardx.co.uk/sites/default/files/datasheets/GardX%20Conserver-%20Material%20Safety%20Data%20Sheet.PDF.pdf.

Garg, H. P., & Mann, H. S. (1976). Performance studies on a solar still with a basin type collector. *Solar Energy*, 18, 159–164. https://doi.org/10.1016/0038-092X(76)90052-9

Ithape, P. K., Barve, S. B., & Nadgire, A. R. (2017). Climatic and Design Parameters Effects on Productivity of Solar Stills: A Review. *International Journal of Current Engineering and Scientific Research*, 4(7), 2394-0697; http://troindia.in/journal/ijcesr/vol4iss7/17-23.pdf

Jadhav, M. V. (2011). Performance of Black Granite Basin Solar Still: A Comparative Study. *Int J Engg Techsci*, 2(2), 161-168. http://www.techsciencepub.com/ijets/docs/Archives_1/vol2issue2/ijets2011020206.pdf

Jamal, W., & Siddiqui, M. A. (2012). Effect of water depth and still orientation on productivity for passive solar distillation. *International Journal of Engineering Research and Applications*, 2(2), 1659-1665. https://www.ijera.com/papers/Vol2_issue2/JW2216591665.pdf

Kabeel A. E., Abdelgaied M., and Eisa A. (2018). Effect of graphite mass concentrations in a mixture of graphite nanoparticles and paraffin wax as hybrid storage materials on performances of solar still. *Renew. Energy*. 132, 119-128 https://doi:10.1016/j.renene.2018.07.147

Khafaji, H. Q. A., Abdul Wahhab, H. A., Al-Maliki, W. A. K., Alobaid, F., & Epple, B. (2022). Energy and Exergy Analysis for Single Slope Passive Solar Still with Different Water Depth Located in Baghdad Centre. *Appl. Sci*., 12, 8561. https://doi.org/10.3390/app12178561

Khalifa A. J. N. and Hamood A. M. (2009). Performance correlations for basin type solar stills. *Desalination* 249 (2009) 24–28; https://doi:10.1016/j.desal.2009.06.011

Khalifa A. J. N. and Hamood A. M. (2009). On the verification of the effect of water depth on the performance of basin type solar stills. *Solar Energy* 83 (2009) 1312–1321; https://doi.org/10.1016/j.solener.2009.04.006

Kalita, P., Dewan, A. N., & Borah, S. (2016). A review on recent developments in solar distillation units. *Sadhana*, 41(2), 203-223. https://doi.org/10.1007/s12046-015-0445-8

Khalifa, A. J., & Hamood, A. M. (2009). On the verification of the effect of water depth on the performance of basin type solar stills. *Solar Energy*, 83, 1312–1321. https://doi.org/10.1016/j.solener.2009.04.006

Kumar, D., Layek, A., & Kumar, A. (2020). Performance enhancement of single slope solar still integrated with flat plate collector for different basin water depth. *AIP Conference Proceedings*, 2273, 050007. https://doi.org/10.1063/5.0024247

Manchanda, H., & Kumar, M. (2015). A comprehensive decade review and analysis on designs and performance parameters of passive solar still. *Renewable*, 2(1), 17. https://doi.org/10.1186/s40807-015-0019-8

Meteoblue. (2022, September). Zakho, Iraq - Monthly weather archive - September 2022. Meteoblue. https://www.meteoblue.com/en/weather/historyclimate/weatherarchive/zakho_iraq_89570?fcstlength=1m&year=2022&month=9

Mohamed, A. H., Shmroukh, A. N., & Attalla, M. (2021). Optimum Seawater Depth in Modified Solar Still Using Vertical Flax Porous Media. *Proceedings of the 5th International Conference on Energy Engineering* December 24 – 26 – Aswan – Egypt.

Muftah, A. F., Alghoul, M., Fudholi, A. A., Abdul-Majeed, M. M., & Sopian, K. (2014). Factors affecting basin type solar still productivity: A detailed review. *Renewable and Sustainable Energy Reviews*, 32, 430–447. https://doi.org/10.1016/j.rser.2013.12.052

Naveenkumar, R., Shanmugam, S., & Veerappan, A. B. (2022). Influence of basin water depth in the distilled yield of traditional and developed passive single basin double slope solar still. *World Journal of Engineering*. https://doi.org/10.1108/WIE-08-2022

OPTICS-PRO.com. (2023). TFA Weather Station Nexus. Retrieved from https://www.optics-pro.com/instruments/tfa-weather-station-nexus/p,13963

Panchal, H., Patel, D. K., & Patel, P. (2018). Theoretical and experimental performance analysis of sandstones and marble pieces as thermal energy storage materials inside solar stills. *Int. J. Ambient Energy*, 39(3), 221-229. https://doi.org/10.1080/01430750.2017.1298059

Panchal, H., Patel, P., Patel, N., & Thakkar, H. (2015). Performance analysis of solar still with different energy-absorbing materials. *International Journal of Ambient Energy*, 36(2), 99-106. https://doi.org/10.1080/01430750.2014.906464

PCE Instruments UK Ltd. (n.d.). Solar radiation meter PCE-SPM 1. Retrieved April 27, 2023, from http://www.industrial-needs.com/technical-data/solar-radiation-meter-pce-spm1.htm

Phadatare, M. K., & Verma, S. K. (2007). Influence of water depth on internal heat and mass transfer in a plastic solar still. *Desalination*, 217(1-3), 267-275. https://doi.org/10.1016/j.desal.2006.09.003

Peng, G., Sharshir, S. W., Hu, Z., Ji, R., Ma, J., Kabeel, A. E., Liu, H., Zang, J., & Yang, N. (2021). A compact flat solar still with high performance. *International Journal of Heat and Mass Transfer*, 179, 121657. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121657

REOTEMP Instruments Cooperation. (2023). Type K thermocouple. Retrieved April 27, 2023, from https://www.thermocoupleinfo.com/type-k-thermocouple.htm#:~:text=Type%20K%20Accuracy%20(whichever%20is,%2B%2F%2D%201.1C%20or%200.4%25

Sakthivel, M., & Shanmugasundaram, S. (2008). Effect of energy storage medium (black granite gravel) on the performance of a solar still. *International Journal of Energy Research*, 32(1), 68-82. https://doi.org/10.1002/er.1335

Shanmugan, S., Janarthanan, B., & Chandrasekaran, J. (2012). Performance of single-slope single-basin solar still with sensible heat storage materials. *Desalination and Water Treatment*, 41(1-3), 195-203. https://doi.org/10.1080/19443994.2012.681832

Singh, S. K., Mittal, M. K., & Sharma, D. (2022). Thermal performance enhancement of basin-type solar still coupled with mini solar pond and shallow solar pond in closed cycle mode. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 44(3), 388-401. https://doi.org/10.1080/15567036.2021.1995784

Taghvaei, H., Jafarpur, K., Estahbanati, M. R. K., Feilizadeh, M., & Ardekani, M. A. S. A. (2014). Thorough investigation of the effects of water depth on the performance of active solar stills. *Desalination*, 347, 77-85. https://doi.org/10.1016/j.desal.2014.06.012

Tahir, A. M. (1997). Desalination of salty water by solar energy (M.Sc. thesis). College of Engineering, University of Technology, Iraq https://iqdr.iq/search?print&view=7a5d598f622ab465fe9cf54777f32339&lang=en

Tanaka, H., Yamashita, A., & Watanabe, K. (1982). Solar distillation with a heat pipe. *Solar World Forum*, 2. https://doi.org/10.1007/978-94-009-3797-0_2

Tiwari, A., & Tiwari, G. (2006). Effect of water depths on heat and mass transfer in a passive solar still: in summer climatic condition. *Desalination*, 195, 78-94. https://doi.org/10.1016/j.desal.2005.11.014

WiNSO. (No date) WiNSO Professional Quick Wax [Product description]. Retrieved April 29, 2023, from https://winso.pl/en/product/402-402_402_wax_500_waterless_wax.

Younis, O., Hussein, A. K., Attia, M. E. H., Aljibori, H. S. S., Kolsi, L., Togun, H., Ali, B., Abderrahmane, A., Subkrajang, K., & Jirawattanapanit, A. (2022). Comprehensive review on solar stills-latest developments and overview. *Sustainability*, 14, 10136. https://doi.org/10.3390/su141610136

Zaki, G. M., El-Dali, T., & El-Shafiey, M. (1992). Improved Performance of a Solar Still. Faculty of Engineering, Tripoli, Libya https://www.ahlia.edu.bh/faculty/prof-shawqi-mohamed-al-dallal-2/

Zaki, G. M., Fatani, A., & Al-Turki, A. (1992). Solar still productivity enhancement using external heat storage. *TRSCE,* 19. https://doi.org/10.1016/0960-1481(92)90037-f

Zein, M., & Al-Dallah, S. (1993). Solar desalination correlation with meteorological parameters. Physics Department, University of Bahrain. https://www.amazon.ca/Solar-Energy-Prospect-Arab-World/dp/0080325734