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Effect of Photostability of Dyes on Enhancing the Productivity of Solar Stills

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ABSTRACT

Solar water distillation has become a promising, environmentally- friendly water purification device that uses solar energy as a source for the energy required. In the present article dyes are added to water basin of the solar stills to increase the absorptivity of water for the solar irradiation thus raising its temperature and hence raising its productivity. Three dyes of different photo-stability are used and are compared with respect to its hourly productivity, total productivity, efficiency and its production behavior along the day. The dyes used are: Black Naphthylamine 10 BR (referred to as Black Dye), Dark Green Dye (referred to as Green Dye) and Red Carmoisine BA Ex (referred to as Red Dye). The variables studied are: type and concentration of dye, depth of water in the basin, time of the day and intensity of solar radiation. Results showed that the highest daily productivity of 2740 ml/m^2 is given by the Black dye solution of 200 ppm concentration. Percentage reduction of still productivity due to increasing water depth from 2 to 3 cm was 12.77, 8.95 and 9.17% for the Black, Green and Red dye solutions, respectively. The percentage increase in total still productivity due to the use of dyes was 37.55, 29.02 and 20.48%, for the Black, Green and Red dyes solutions, respectively; compared to the reference still. The enhancing effect of the Black dye was mostly pronounced in the morning period since its photo-stability (expressed by the degradation half-life period) is much less than the other two dyes.

Keywords: Solar still, productivity, enhance, dye, photo- stability

1.INTRODUCTION

This section presents a theoretical background on the subject of study.

Enhancing solar desalination

Fresh water is a vital component for life. However, about 97% of the water available on Earth is salty water. Thus, feasible techniques should be developed for desalinating water. One such a technique is water distillation; which is known to require huge amount of energy. For this reason great attention has been made by researchers towards solar desalination. Besides being a means for saving fossil fuel, solar desalination has the added advantage of being an environmentally- friendly technique. Means of enhancing the productivity of solar stills have been developed and studied extensively.

Different theoretical and experimental studies carried out in the field of solar distillation, with green-house effect,

have shown that global efficiency of a simple solar still is affected by physical and building parameters, especially by the difference of temperature between the evaporation surface and that of the condensation surface [1, 2].

Using black rubber or black gravel materials within a single sloped solar still as a storage medium is examined. The experimental results showed that black rubber (10 mm thick) improves the productivity by 20% at the conditions of 60 l/m^2 brine volume and 15° glass cover angle. Also, using black gravel of 20–30 mm size improves the productivity by 19% at the conditions of 20 l/m^2 brine volume and 15° of glass cover angle [3].

The evaporation rate from a still can be increased effectively by coating the still base with photo-catalyst materials, or by pre-heating the inlet water to the still. The easily available Granular Activated Carbon, GAC, is one of the best photocatalyst materials suitable for the solar-still for enhancing the evaporation rate. Solar-pond technology is the renewable and efficient technology for pre-heating the inlet water to solar still. Hence by the combination of GAC coating and solar pond technology the evaporation rate can be increased considerably, hence the efficiency of solar still is increased [4, 5]. Metallic energy storage materials have also been used in this concept [6].

In order to improve the performance and efficiency of inclined solar stills (ISS), numerous works have been incorporated by increasing the free surface area of water. The distillate yield collected from the passive ISS was found as 1000–8100 mL/m^2 whereas active ISS produced a distillate yield of 1045–9000 mL/day [7].

In Active Solar Still, basin water temperature is increased to improve the evaporation rate. This can be done by the following methods: waste hot water can be directly fed into still basin & Hot water generated from the collector panels or the concentrator can be fed into the still basin & energy storage materials can be utilized [8, 9].

It should be pointed out that the distillate output depends both on the brine surface temperature and the temperature difference (ΔT) between the brine surface and the glass cover [10]. Thus with higher surface temperature, Ts, there is greater evaporation. However, the driving potential ΔT controls evaporation.

A study was made on using dyes for enhancing solar desalination. It was important to ascertain whether there is any carry-over of the dye molecules in the distillate [11]. From the absorbance spectrum of the distillate there is no evidence of such carry over [12]. This is to be expected since the maximum surface temperature recorded for the dye solution was 60°C whereas the boiling points of these dyes are of the order of 180°C and more [13]. Thus only water evaporates.

A researcher has finished a project on using nano-material for enhancing solar desalination. The main goal of this project was to fabricate and test a composite of different concentrations of silver nanomaterials and Graphene to enhance the photothermal conversion which would enhance the rate of water vaporization. It is worthy to state that silver nanoparticles have super antibacterial effect. This means that the obtained water is pure and clean not only from salt and impurities but also from all bacteria and microorganism [14].

A study investigated improvement in the performance of a solar still with the integration of a geothermal cooling system and a vacuum pump. Cooling is achieved by circulating water underground. As a result of this circulation, the cold fluid from the ground flows into a counter flow shell and tube heat exchanger. A 305% increase in daily water productivity resulted from the proposed enhancement technique [15].

An investigation is made on the effect of integrating a simple solar collector, floatable black wicks, and orientation as modified double-slope solar still (MDSSS), and compared its performance with conventional double-slope solar still (CDSSS). For the east-west orientation, preheating, and floatable black wicks, the total yield of MDSSS exceeded the CDSSS by 45.65%. And at the same conditions, the daily average efficiency of southern and northern sides of MDSSS was 25.33 and 37.25%, while for CDSSS, it was 13.87 and 30.73%, respectively [16].

A numerical model is presented to estimate the performance of solar basin type distillation systems, both for conventional passive solar stills and active (forced circulation) stills with enhanced heat recovery [17].

A new technique is explored for improving the performance of solar stills (SSs) through utilizing three different types of a new hybrid structure of heat localization materials (HSHLM) floating on the water surface to increase the evaporation rate as well as water production and minimize heat losses. The three types were exfoliated graphite flakes with wick (type A), carbon foam with wick (type B), and exfoliated graphite flakes with wick and carbon foam (type C). The obtained results showed that the daily productivity was enhanced by 34.5, 28.6 and 51.8% for type A, type B and type C, respectively, relative to the conventional one [18].

Researchers modified, developed and tested existing design of single slope solar still. The modifications in conventional single slope solar still included (i) inside walls painted with white color and (ii) attachment of water sprinkler with constant water flow rate of 0.0001 kg/s on the glass cover. The distilled water output recorded was 2940 ml and 3541 ml from conventional and modified solar stills, respectively. Water productivity or yield of single slope solar still is increased by 20% from the above modifications.

The overall efficiency is increased by 21% over the conventional solar still [19].

A number of researchers reported the recent progress in solar absorber material design based on various photothermal conversion mechanisms. These articles aim to provide a comprehensive review on the current development in efficient photothermal evaporation, and suggest directions to further enhance its overall efficiency through the judicious choice of materials and system designs, while synchronously capitalizing waste energy to realize concurrent clean water and energy production [20-22].

1.1. Fundamental mechanisms of photo-thermal conversion

Solar energy can be harnessed and converted into various kinds of energy forms including electricity, chemical (fuels), and thermal energy through photovoltaic, photochemical, and photothermal processes, respectively. Among these technologies, photothermal is a direct conversion process that possesses the highest achievable conversion efficiency. The photothermal effect is produced by photoexcitation resulting in partial or complete thermal energy production. This effect can be observed in inorganic materials, such as noble metals and semiconductors, as well as organic materials such as carbon-based materials, dyes and conjugated polymers.

1.2. Photostability of dyes

The photostability of a substance may be defined as the response of the material to the exposure to solar, UV, and visible light in the solid, semisolid, or liquid state that leads to a physical or chemical change [23].
Additionally, the half-life ($T_{1/2}$, in hours) is the time required to photodegrade half of the initial dye concentration, which is used to quantitatively compare the photo-degradation reaction, and it increases with the initial concentration of dye molecules. It is assumed that the driving force of degradation is constantly proportional to the dye concentration [24, 25].

2. EXPERIMENTAL WORK

The present work is conducted in the Solar Energy Lab. of Faculty of Engineering, Minia University, Minia, Egypt. Minia is located at Latitude: 28.1099 and Longitude: 30.7503. The work is performed during the months April-July, 2019.Four identical basin –type solar stills are used throughout the experimental work. Stills are manufactured of galvanized iron and each still has an effective base area of 1 m^2 and is fitted with a glass cover tilted with an angle 30.7 to the horizontal. A distillate channel is provided at the edge of each still basin for collecting the distillate. One of these stills is used as a reference still while the other three stills are used for studying the behavior of different dyes. Experiments are run through April- July, 2019. A schematic drawing of one still is shown in Fig. 1. Thermocouples were located in different places of the still to record temperature at different locations such as: glass cover temperature (inlet and outlet) and water temperature in the basin, A standard thermometer is suspended in the still enclosure to measure the vapor temperature before it reached the glass cover and being condensed and another for measuring ambient temperature.

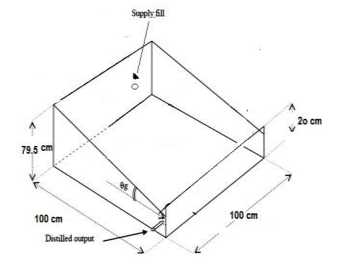


Figure 1: Schematic drawing of the basin-type solar still

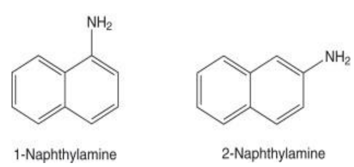
2.1. Material and method

This section presents the materials used throughout the experimental work and the procedure followed in the work.

2.1.1. Material

Distilled water is used throughout the experiments.
Sodium chloride salt: used for preparing the saline solution.
The dyes used in the present study are water soluble dyes.
These are [26]:

Napthylamine 10 BR (Black)

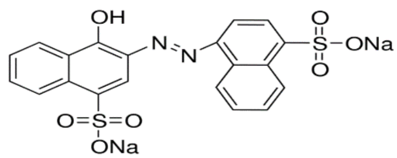


Molecular formula: $C_{22}H_{16}N_6NaO_9S_2^{+}$

Molecular weight: 595.5

Photo-degradation half- life period ($T_{1/2}$): The half-life for the photo-degradation reaction of this dye in air is estimated to be 1.9 h [27].

Carmoisine BA Ex (Red)

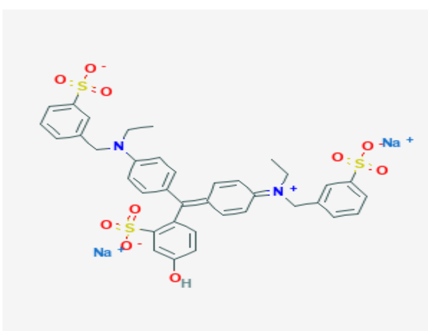


Synonym: Acid Red 14, Chromotrope FB, Disodium 4-hydroxy-3-[(4-sulfo-1-naphthalenyl)azo]-1-naphthalenesulfonate, Mordant Blue 79.
Empirical Formula: $C_{20}H_{12}N_2Na_2O_7S_2$
Molecular Weight: 502.43
Photo-degradation half-life period: 11.9 ± 1.6

- **Fast Green Dye**

  Dark green powder or granules with a metallic luster [28].

Synonyms
Food Green 3
Green No. 3



Molecular Formula: $C_{37}H_{34}N_2Na_2O_{10}S_3$
Molecular weight: 808.9 g/mol
Photo-degradation half-life ($T_{1/2}$) = 18.4±3.3h.
Dyes concentrations tested are: 100, 200, 300, 400 and 500 ppm.

2.1.2. Method

Four solar stills are used in the experimental work and are fitted with temperature measuring devices. Salty water (3000 ppm salt) is fed to the stills such as it gives water depth of 2, 3 or 4 cm; according to requirements. In each test one solar still is kept with saline water only and is used as a reference still while dyes, with a specified concentration, is added to the other three stills for comparison. The hourly yield from each still, ml/m^2/h, is recorded and the total productivity along the working hours is obtained by collecting these amounts.

2.2. Instrumentation

Solarimeter, Model: HANNI, SOLAR 130; with a conversion factor: 100mV/1000W/m^2, is used for measuring the intensity of solar irradiation and a digital thermometer is used to measure temperatures at various locations. It measures in the range -10 to 110^{O}C.

3.RESULTS AND DISCUSSION

The present section presents and analyze the results recorded throughout the experimental work.

3.1. General Behavior of Dye Solution

The object of the present test is to determine the suitable concentration for each dye which gives the best results and should be used in the experimental work.

3.I.1. Determining the best dye concentration to be used

Experiments are run on dye solutions with different concentrations; 100, 200, 300, 400, and 500 ppm concentration and the results are represented in Fig. 2; as a relation between dye concentration and daily productivity. Examination of Fig. 2 shows that the still productivity increases with increasing dye concentration till a certain limit of concentration where the productivity either decreases or keeps constant. The Black Dye gave the maximum productivity from a dye solution of 200 ppm. Black dye solutions of concentration higher than 200 ppm tend to be opaque, thus reducing the transmissivity of the solution for the passage of solar radiation and consequently reducing the rate of water evaporation. This effect becomes more obvious for more dark dyes; i.e., Black dye in the present study. For Green and Red dyes, this is not as obvious as it is for the Black dye. A very slight increase in still productivity is noticed when increasing dye concentration beyond 400 ppm. The recorded daily productivity was: 2740 ml/m^2, 2590 ml/m^2 and 2420 ml/m^2 for stills with Black, Green and Red dyes, respectively at dye concentration 200 ppm for the Black dye and 400 ppm for the Green and Red dyes. Thus, other experiments were run on 200 ppm Black dye solution and 400 ppm for the Green and Red dye solutions.

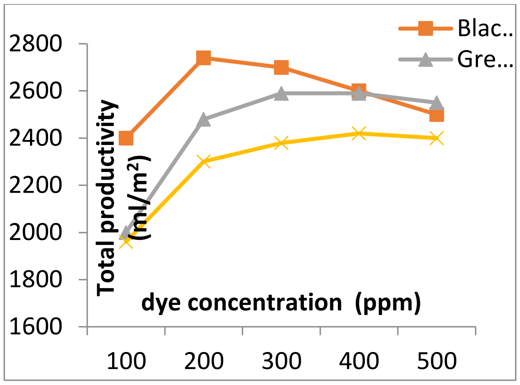


Figure 2: Effect of dye concentration on still total productivity (April 28, 2019)

3.I.2. Effect of intensity of solar irradiation on still productivity

This test is run on 9 June, 2019. The results of this test are given in Fig. 3. which shows the relation between local time in one side and the hourly productivity and intensity of solar irradiation on the other side. Examination of Fig. 3 indicates that an increase of solar intensity is accompanied by an increase in still productivity. The same trend is shown by the three kinds of dyes tested. The Black dye solution gave the highest productivity followed by the Green dye solution and lastly by the Red dye solution. The maximum hourly productivity is noticed around solar noon when maximum solar intensity prevails. The maximum yield obtained for the Black, Green and Red dye solutions were 630, 510 and 470 $ml/m^2/h$, respectively at a maximum value for solar irradiation intensity 1098 W/m^2 at solar noon. In the first couple of hours the Black dye solution gave much higher productivity compared to the Green and Red dye solutions. However, at about 13:30 the rate of production from the still with Black dye solution drops sharply. This is because the photo-stability of the black dye is not as high as that of the Green and Red dyes. The degradation half-life time of the Black dye is 100 min. [27] as compared to that of Green dye (18.4±3.3 h) and of Red dye (11.9±1.6 h) [28]. Thus, the Black dye results in high positive effect on enhancing the solar productivity at the beginning of the experiment but after about 2 hours the productivity decreases sharply due to its photo-degradation. In spite of this, the Black dye, as a whole, gave the highest daily productivity of 2740 ml/m^2 compared to 2590 and 2420 ml/m^2 for the Green and Red dyes, respectively. Solar energy is absorbed in a very thin upper layer, thus raising the surface temperature of the brine and increasing the productivity of the still.

The same attitude is shown by the three dyes tested and therefore no further tests are run on the effect of solar intensity on still productivity.

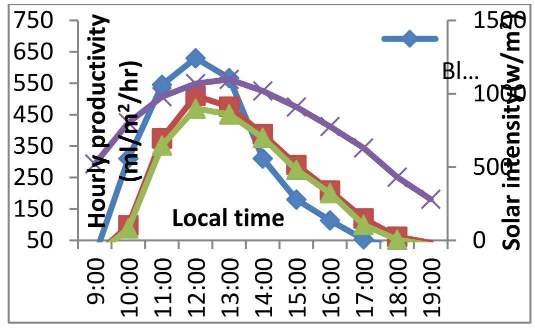


Figure 3: Change of hourly still productivity with solar intensity for different dyes (Minia, Egypt, 9/6/2019)

3.2. Experimentation on specified stills

Experiments are run on stills having Black, Green or Red dye as well as on a still having saline water without dye; which is used as a reference.

3.2.1. Experimentation on the reference still

The results obtained from experimentation on the reference still are given and discussed below.

A. Temperature distribution in the solar still

Figure 4 presents the temperature distribution among the reference still during experimentation. Examination of Fig. 3. shows that the highest temperature is recorded by the still basin followed by the outside glass temperature, the vapor temperature and the inside glass temperature. The temperature gradient between the basin temperature and the inside glass cover temperature is also given. This temperature has a special importance since it represents the driving force for the production of desalinated water. This temperature gradient gives the difference between the temperature of evaporation surface (basin) and condensation surface (inside glass cover). The highest value for this temperature gradient was 12^{O}C and it was obtained at solar noon. The highest basin temperature was 51^{O}C and it is obtained a slightly after solar noon. All temperatures have the same attitude, i.e., higher values around solar noon and lower values at the beginning and end of the day.

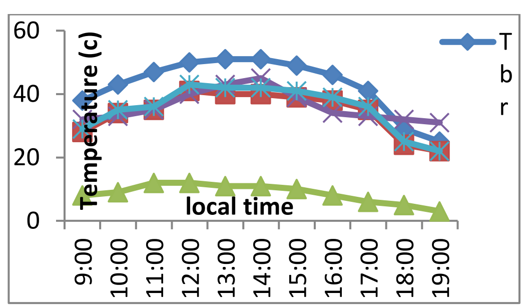


Figure 4: Change of temperature with local time for reference still (30/6/2019)

B. Hourly and daily productivity of the reference still

This test is run on 30 June, 2019. The results of this test are represented in Fig. 5, as a relation between hourly and daily still productivity and local time. Examination of figure 4 clarifies that the maximum hourly productivity is achieved at solar noon where maximum solar intensity is satisfied. A productivity of 450 $ml/m^2/h$ is obtained from the reference still at solar noon (intensity of solar irradiation 1130 $W/m^2/h$). As sunset hours are approaching the increase in total still productivity becomes less sharp than it was in the morning period (before solar noon). This is due to depletion of solar irradiation as sunset hours are approached. The daily productivity accomplished by the reference still was 1992 ml/m^2.

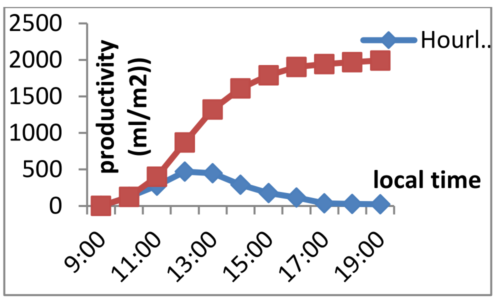


Figure 5: Change of still productivity with time (Reference still, 30/6/2019, water depth 2cm)

C. Change of still productivity with water depth in the basin

Stills with different water depths in the basin; 2, 3 and 4 cm, are used and tested under the same environmental conditions. The results of this test are shown in Fig. 6. Examination of this figure shows that the still productivity is reduced as the depth of water is increased. This is because of lower basin temperature attained for larger amount of water in the basin. The reference still daily productivity was 1992 ml/m^2 for a water depth of 2 cm, compared to 1784 and 1686 for stills with 3 and 4 cm water depth, respectively. This is equal to a reduction of 10.44% due to an increase in water depth from 2 to 3 cm and a reduction of 15.36% due to its increase to 4 cm.

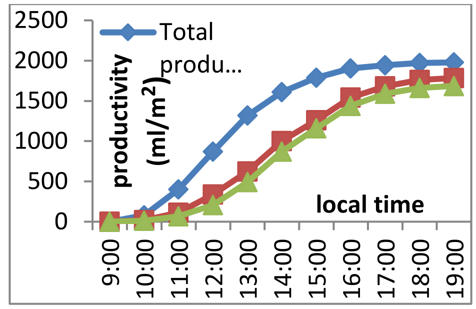


Figure 6: Change of still total productivity with water depth (reference still, 5/7/2019)

D. Variation of still efficiency along the day

The still efficiency is calculated from the equation:

$H = h_{fg} \times \sum M / As \times I$

Where (I) is the daily solar radiation, (M) is the total productivity of the day, (hfg) is the latent heat of vaporization, (As) is the still area.

The still efficiency is calculated at hourly intervals and the values are represented in Fig. 7.

Examination of this figure indicates that the still efficiency satisfies higher values around solar noon; with rapidly increasing values in the morning period and slowly decreasing values at the afternoon period. A highest still efficiency of 24.58% around solar noon is recorded for the reference still. In the morning period and around solar noon, ambient temperature is often higher than at the afternoon period. Thus less thermal losses take place, leading to higher values for still efficiency.

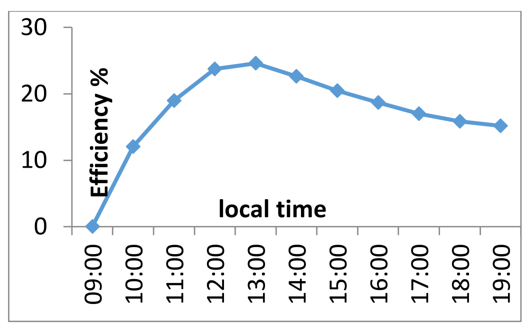


Figure 7: Change of still efficiency with local time (Reference still, 30/6/2019)

3.2.2. Experimentation on still with Black dye

Black Naphthylamine Dye (referred to as Black dye) is used in this test. Experiments are run on 200 ppm Black dye solutions since this concentration has indicated to give the highest still productivity.

A. Temperature distribution in the solar still

Temperatures of: basin, vapor, inside glass cover and outside glass cover are recorded and presented in Fig. 8 as well as the temperature gradient between basin temperature and inside glass cover temperature. The various temperatures have higher values around solar noon. Highest basin temperature reached was 57^{O}C in the vicinity of solar noon (compared to 51^{O}C for the reference still). The highest temperature gradient satisfied was 17^{O}C immediately after solar noon (at 13:00), compared to 12^{O}C for the reference still.

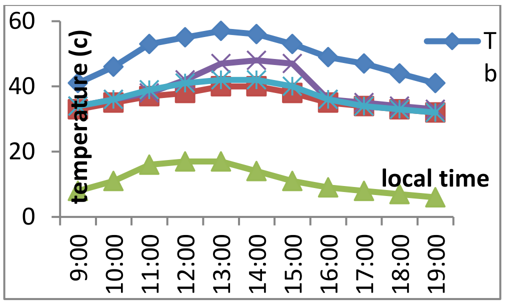


Figure 8: Change of temperature with local time
(still with 200ppm of Black dye, 30/6/2019)

B. Change of hourly and daily still productivity with local time

This test is run on 30 June, 2019. The results of this test are represented in Fig. 9, as a relation between hourly and daily still productivity and local time. Examination of figure 8 clarifies that the maximum hourly productivity is achieved at solar noon where maximum solar intensity is satisfied. A productivity of 630 ml/m^2/h is obtained from a 200 ppm Black dye solution at solar noon (intensity of solar irradiation 1130 W/m^2/h). As sunset hours are approaching the increase in total still productivity becomes less sharp than it was in the morning period (before solar noon). This is due to depletion of solar irradiation as sunset hours are approached. An extra reason which is specially noticed when using Black dye is the photo-degradation taking place when the Black dye is exposed to solar irradiation. This results in lowering dye concentration in the basin, thus lowering the rate of evaporation and consequently the productivity in the afternoon period. Only a slight increase in still productivity in noticed in the few hours prior to sunset hour. It is noticed that 74.85% of the daily productivity is accomplished in the period from 9 to 13:00 and only 25.15% is accomplished in the period 13:00 to 19:00. A total still productivity of 2740 ml/m^2 is satisfied through the period 9:00 to 19:00.

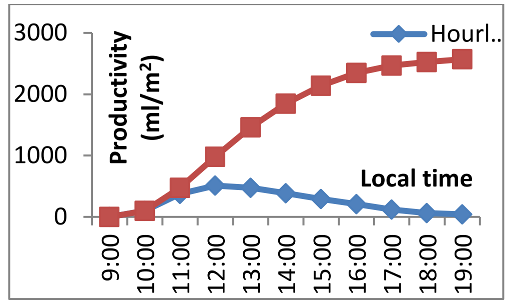


Figure 9: Change of productivity with time
(Still with 200 ppm Black dye, 30/6/2019)

C. Change of still productivity with water depth in the basin

Solar stills with water depth in the basin of 2, 3 and 4 cm are tested with respect to its hourly productivity. The results of this test are given in Fig. 10. Examination of Fig. 10 indicates that still productivity becomes lower as the depth of water in the basin is higher. A specified amount of solar irradiation falling on water raises its temperature to a higher degree when its depth is smaller; since a smaller value for water depth means smaller amount of water thus, higher increase in water temperature. This leads to an increase in the rate of evaporation thus, increasing still productivity. The attitude of these results agrees with the results reported in [29, 30]. A daily still productivity of 2740 ml is obtained from a still with water depth of 2 cm while the corresponding values are 2390 ml and 2278 ml for stills with water depths 3 and 4 cm, respectively. So, a decrease of 12.77% in still productivity took place as a result of increasing water depth from 2 to 3 cm. The corresponding value is 16.86% when increasing water depth from 3 to 4 cm. These values are relatively higher than its corresponding values for the reference still and it may be due to the added effect of reducing water transmissivity for solar irradiation as a result of increasing water depth in the presence of dye.

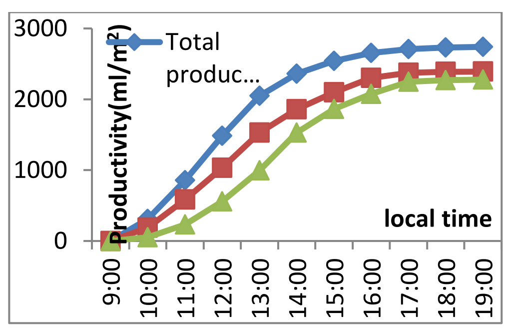


Figure 10: Change of still total productivity with water depth
(Still with 200 ppm Black dye, 6/7/2019)

D. Change of still productivity with temperature gradient

As mentioned earlier, the temperature gradient between basin water temperature and inside glass cover temperature is the driving force for the production of desalinated water. In the present test, still hourly productivity, as well as temperature gradient are plotted versus local time as given in Fig. 11. Examination of this figure indicates that still hourly productivity changes in accordance to the temperature gradient between still basin and inside glass cover temperature. The period following local time 13:30 showed a sharp depletion in still productivity and in temperature gradient due to photo-degradation of the Black dye. A maximum hourly productivity of 630 ml/m^2/h is obtained at the highest temperature difference of 17^{O}C.

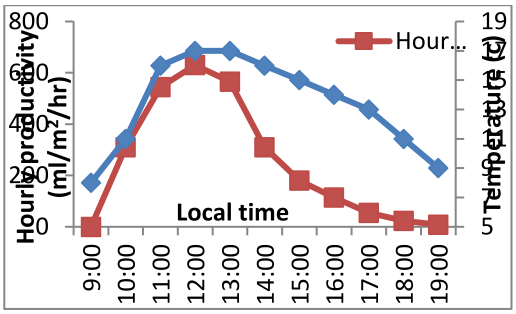


Figure 11: Change of hourly still productivity with temperature difference (Tb-Tgi) (Still with 200 ppm Black dye, 30/6/2019)

E. Variation of still efficiency along the day

The results of this test are given in Fig. 12. The shape of the curve in Fig. 12 indicated that higher still efficiency is accomplished around solar noon; after which the values decline sharply due to approaching sunset hours and to partial photocatalytic degradation of the Black dye which leads to less absorption of solar irradiation thus, lower productivity. The highest efficiency obtained was 40.49% at solar noon.

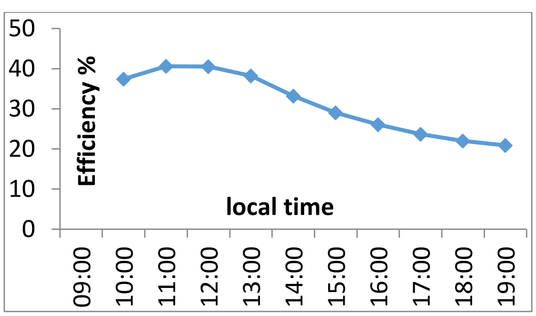


Figure 12: Change of still efficiency along the day (Black dye, 200 ppm, 30/6/2019)

3.2.2. Experimentation on still with Green dye

The following paragraphs give the results of experimentation on Green dye.

A. Temperature distribution in the solar still

During experimentation on the Green dye, temperatures in various locations are recorded such as it includes basin temperature (Tb), inside glass temperature (Tgi), outside glass temperature (Tgo) and vapor temperature (Tvap.). In addition, the temperature gradient between basin temperature and inside glass cover temperature is plotted against time. Figure 13 shows the temperature distribution of a solar still working with Green dye solution along the day. It is clear that the value of the temperature gradient becomes larger around solar noon. Thus, highest values of 15^{O}C are recorded for the period 12:00 to 14:00. The corresponding value for the still with Black dye was 17^{O}C. Thus, the use of Black dye lead to higher values for temperature gradient resulting in higher still productivity.

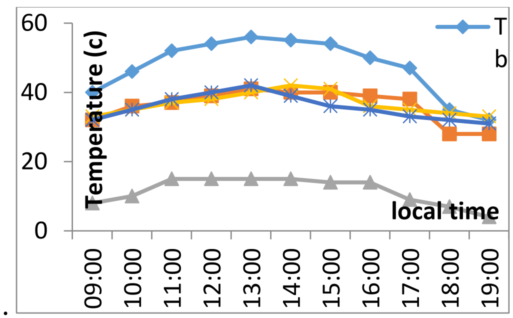


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Figure 13: Change of still temperatures with local time (Still with 400 ppm Green dye solution, 30/6/2019)

B. Change of hourly and daily still productivity with local time

This test is run on 30 June, 2019. The results of this test are represented in Fig. 14, as a relation between hourly and daily still productivity and local time. Examination of figure 14 clarifies that the maximum hourly productivity is achieved at solar noon where maximum solar intensity is satisfied. A productivity of 510 ml/m^2/h is obtained from a 400 ppm Green dye solution at solar noon (intensity of solar irradiation 1130 W/m^2/h). As sunset hours are approaching the increase in total still productivity becomes less sharp than it was in the morning period (before solar noon). This is due to depletion of solar irradiation as sunset hours are approached. The total productivity obtained from the still with Green dye solution was 2570 ml/m^2, compared to 2740 ml/m^2 for the still with Black dye solution. Thus, although the Green dye has higher photo-stability but its yield is less than that of the still with Black dye solution. This may be due to lower absorptivity of the green solution to solar irradiation compared to the black one.

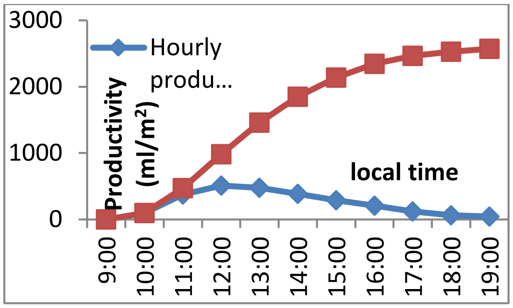

Figure 14: Change of hourly and daily still productivity with time
(Still with 400 ppm Green dye solution, 30/6/ 2019)

C. Change of still productivity with water depth in the basin

Solar stills with water depth in the basin of 2, 3 and 4 cm are tested with respect to its hourly productivity. The results of this test for the Green dye are given in Fig. 15. Examination of Fig. 15 indicates that still productivity becomes lower as the depth of water in the basin is higher. The attitude of these results agrees with the results given in [29, 31]. A daily still productivity of 2570 ml is obtained from a still with water depth of 2 cm while the corresponding values are 2340 and 2210 ml for stills with water depths 3 and 4 cm, respectively. These values are lower than those obtained for the still with Black dye solution.

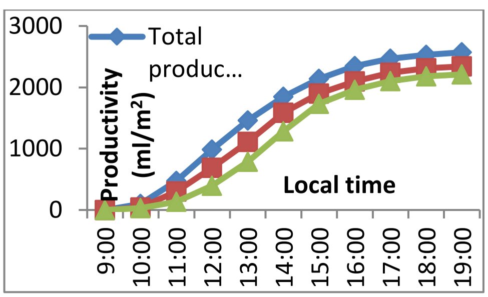

Figure 15: Change of still total productivity with water depth (Still with 400 ppm Green dye, 7/7/2019)

D. Change of still productivity with temperature gradient

Figure 16 presents the change of hourly still productivity with temperature gradient between basin temperature and inside glass cover temperature. It is clear that the still productivity is proportional to the temperature gradient, i.e., higher still productivity is accomplished as the temperature gradient is higher. A maximum hourly still productivity of 510 ml is obtained at a maximum temperature difference of 15^{O}C at solar noon. This agrees with the work of [32]. A higher temperature gradient means higher basin temperature and lower inside glass cover temperature, i.e., enhancement for the evaporation of basin water and enhancement for the condensation of the vapor formed, i.e., an enhancement for the desalination process as a whole.

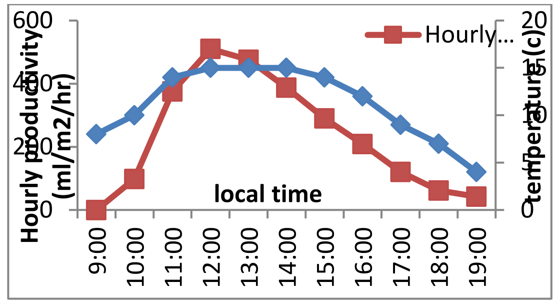

Figure 16: Change of still productivity with temperature gradient
(30/6/2019)

E. Variation of still efficiency along the day

The still efficiency is calculated periodically each hour and the estimated values are recorded versus local time as shown in Fig. 17.

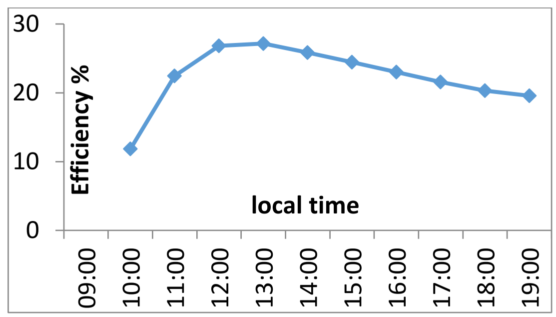

Figure 17: Variation of still efficiency along the day
(Green dye, 30/6/2019)

The shape of the curve in Fig. 17 indicates that still efficiency rises in the morning period till it reaches its maximum value at solar noon after which it declines smoothly as sunset hour is approached. The highest value obtained for efficiency of the still working with Green dye solution was 27.16% and it was reached at 13:00.

3.2.4. Experimentation on still with Red dye

The results obtained for the Red dyes are given in the following paragraphs.

A. Temperature distribution in the solar still

Experiments similar to those run in sections 3.2.1.1, 3.2.2.1, and 3.2.3.1 are run on stills with Red dye solution and the results are recorded. The results showed that the value of the temperature gradient becomes larger around solar noon. Thus, highest value of 14^{O}C is recorded for the period 12:00 to 14:00 and the highest hourly productivity was then 542 ml/m^2/h. The corresponding value for the still with Black dye was 17^{O}C and it produced 630 ml/m^2/h.

Thus, the use of Black dye lead to higher values for temperature gradient resulting in higher still productivity compared to the Red dye.

B. Change of hourly and daily still productivity with local time

This test is run on 30 June, 2019. The results of this test clarify that the maximum hourly productivity is achieved at solar noon where maximum solar intensity is satisfied. A productivity of 470 ml/m^2/h is obtained from a 400 ppm Red dye solution at solar noon. As sunset hours are approaching the increase in total still productivity becomes less sharp than it was in the morning period (before solar noon). The total productivity obtained from the still with Red dye solution was 2400 ml/m^2, compared to 2740 ml/m^2 for the still with Black dye solution. Thus, although the Red dye has higher photo-stability but its yield is less than that of the still with Black dye solution. This may be due to lower absorptivity of the green dye to solar irradiation compared to the Black one.

C. Change of still productivity with water depth in the basin

Solar stills with water depth in the basin of 2, 3 and 4 cm are tested with respect to its hourly productivity. The results of this test for the Red dye indicate that still productivity becomes lower as the depth of water in the basin is higher. The attitude of these results is the same as that of stills working with Black and Green dye and it agrees with the results of Samraj [26], and Ali [32]. A daily still productivity of 2400 ml is obtained from a still with water depth of 2 cm while the corresponding values are 2180 and 2038 ml/m^2 for stills with water depths 3 and 4 cm, respectively. These values are lower than those obtained for the stills with Black dye and Green dye solutions.

D. Change of still productivity with temperature gradient

The results of this test showed that the still productivity is proportional to the temperature gradient, i.e., higher still productivity is accomplished as the temperature gradient is higher. A maximum hourly still productivity of 532 ml/m^2 is obtained at a maximum temperature difference of 14^{O}C at solar noon. This agrees with the results given in [33]. Thus, higher basin temperature and lower inside glass cover temperature means enhancement for the evaporation of basin water and enhancement for the condensation of the vapor formed, i.e., an enhancement for the desalination process as a whole.

E. Variation of still efficiency along the day

The still efficiency is calculated periodically each hour and the estimated values are recorded versus local time. The results of this test indicated that still efficiency rises in the morning period till it reaches its maximum value at solar noon after which it declines smoothly as sunset hour is approached. The highest value obtained for efficiency of the still working with Red dye solution was 25.34% and it was reached at 13:00.

Comparative Study

The experimental results are examined thoroughly and put in the form of Tables and Figures for the object of comparison as follows:

3.2.3. Percentage increase in total still productivity

The percentage increase in productivity due to the use of dyes, compared to the reference still is calculated from the recorded experimental data and is given in Table 1. Calculations are based on both the total productivity at the end of the day and on the productivity till 13:00.

Table 1: Percentage increase in still productivity due to the presence of dyes
(Compared to the reference still, water depth in the basin = 2 cm, 30/6/2019)

	Reference still	**Black dye**		**Green dye**		**Red dye**	
	Productivity	Productivity	% increase	Productivity	% increase	Productivity	% increase
Daily productivity	1992	2740	**37.55**	2570	**29.02**	2400	**20.48**
Productivity till 13:00	1320	2051	**55.38**	1459	10.53	1361	3.11

Examination of the figures in Table 1 indicates that the enhancing effect of the Black dye is more pronounced in the morning period (till 13:00) where 55.38% percentage increase is satisfied in this period; compared to an increase of 37.55% when calculations are made for the entire day. So, it is recommended that Black dye be used when a limited amount of desalinated water is required urgently. The enhancing effect is higher for the Green dye than for the Red dye. An increase of 29.02% is satisfied by the still having Green dye, compared to 20.48 for the Red dye. Calculations based on the productivity till 13:00 gives percentage increase of 10.53 and 3.11% for the Green and Red dyes, respectively. Although experimentation on both the Green and Red dyes was made on 400 ppm dye solutions but the fact that the photo-stability of the Green dye is higher than that of the Red dye led to higher enhancing effect caused by the Green dye.

3.3.2. Effect of water depth in the basin

The results presented in sections 3.2.1.3, 3.2.2.3, 3.2.3.3 and 3.2.4.3 show that the daily still productivity becomes lower as the depth of water in the basin is larger. That negative effect of increasing water depth works along the day; causing a decrease in the total still productivity. The percentage of productivity reduction due to increasing depth of water is given in Table 2. The highest percentage reduction of still productivity of 16.86% is satisfied by the still having Black dye at water depth 4 cm. This is followed by the still with Red dye (15.08%) and lastly by the still with Green dye (14.01%).

Table 2: Effect of water depth on still productivity
(as percentage reduction referred to the reference still)

Water depth, cm	Productivity and % Distillate reduction due to increasing water depth					
	Black dye		Green dye		Red dye	
2	2740		2570		2400	
3	2390	12.77%	2340	8.95%	2180	9.17%
4	2278	**16.86%**	2210	14.01%	2038	15.08%

However, it is interesting to note that the percentage of distillate obtained in the last hour of the day becomes larger as the depth of water is larger. This may be due to larger heat capacity stored in the basin water by larger volume of water; i.e., larger water depth. Moreover, this value of percentage increase in the last hour is larger for the Black dye followed by the Green dye and lastly by the Red dye. This may be due to higher absorbance of solar irradiation of darker colors given by the dyes solutions. These results are given in Table 3. which is summarized from the experimental data represented graphically before. Table 3 presents the productivity in the last hour of the day; represented as percentage to the total productivity of the day and shows how it changes with the water depth in the basin. It is noted that increasing water depth from 2 to 3 cm decreased the productivity in the last hour (as % of the total) but further increase in water depth raises this value a little. This may be due to larger heat capacity contained in larger volume of water beyond 3 cm depth.

Table 3: Effect of water depth on still productivity in the last hour of the day

Dye / Water depth, cm	% Distillate increase in the last hour of the day			
	Black dye	Green dye	Red dye	Reference still
2	1.19	1.63	1.46	1.57
3	0.08	1.29	0.99	1.10
4	0.44	1.37	1.16	1.36

For more clarification, these results are also presented as a plot showing the total productivity of different stills at different water depths as shown in Fig. 18 and Fig. 19 for water depths 3 and 4 cm, respectively for solutions with different dyes.

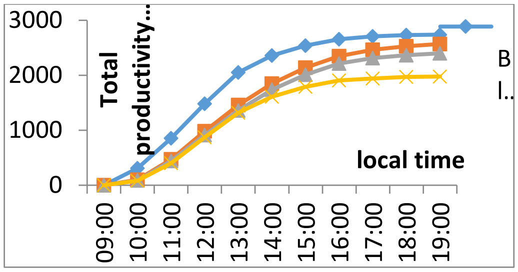

Figure 18: Total productivity of different stills at water depth 3cm

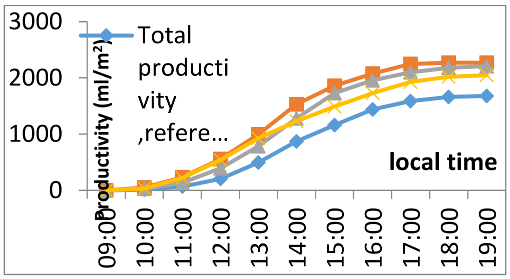

Figure 19: Total productivity of different stills at water depth 4 cm

3.3.3. Effect of use of dyes on still efficiency

Efficiency of stills having different dyes and the reference still is calculated at the end of the day (at 19:00) and at mid-day (at 13:00). Calculation results indicated that efficiency of different stills as well as the reference still is higher when calculated for the morning period than its corresponding values which are calculated for all the day. This means that a higher portion of the product is obtained in the morning period. This is expected due to higher solar intensity in the morning period than in the afternoon period. As a special case, it is noticed that the efficiency of the still having Black dye solution at 13:00 is almost double its value for the entire day (58.18% at 13:00 as compared to 20.88% at 19:00). This is because the high tendency of the Black dye for photo-degradation when exposed to solar irradiation. The calculation results are shown in Table 4 and in Fig. 20 for more clarification.

Table 4: Efficiency of stills at 13:00 and at 19:00

	Reference still	Black dye	Green dye	Red dye
η (at 19:00),%	15.18	20.88	19.58	18.29
η (at 13:00), %	24.58	**38.18**	27.16	25.34

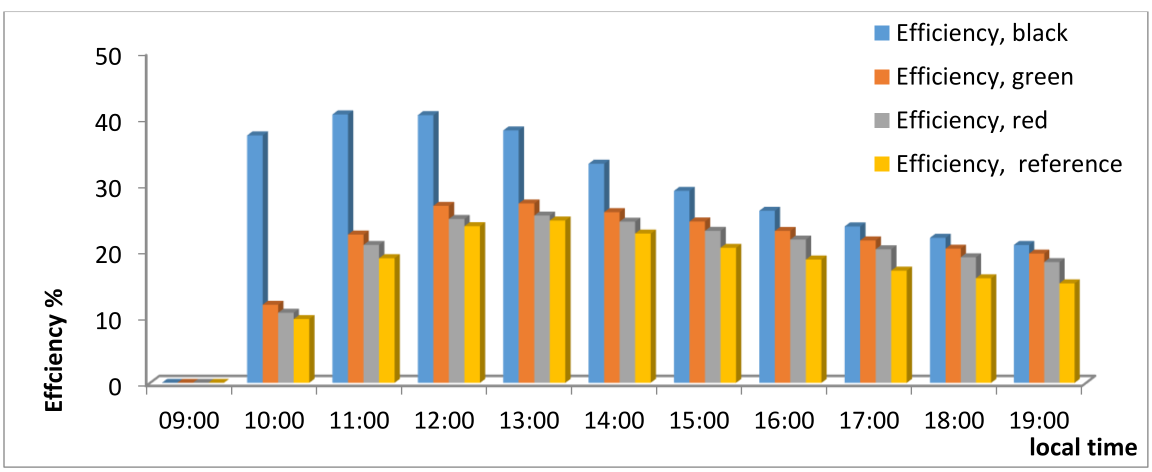

Figure 20: Efficiency of stills throughout the day

4.CONCLUSION

The following conclusions could be made from the recent study on the use of dyes for enhancing solar still productivities. The dyes used are: Black Naphthylamine (referred to as Black dye), dark Green dye (referred to as Green dye) and Carmoisine BA EX Red (referred to as Red dye):

1. The highest daily productivity is given by the Black dye solution of 200 ppm concentration and of Green and Red solutions of 400 ppm.

2. Hourly still productivity is always proportional to intensity of solar irradiation. For the Black dye, most of its productivity is accomplished in the morning period since it is accessible for photo-degradation.
3. Higher values of temperature gradient ($T_{basin} - T_{gi}$) are obtained around solar noon and this was the attitude of the results for stills with different dyes. The highest value recorded was for the still with Black dye solution.
4. For all stills, daily still productivity decreases with increasing water depth in the basin.
5. The reference still gave a total productivity of 1992 ml/m^2 and the corresponding values were 2740, 2570 and 2400 ml/m^2 for the Black, Green and Red dyes, respectively.
6. The reference still recorded its highest efficiency of 24.58% around solar noon. The corresponding values were 40.49, 27.16 and 25.34% for the Black, Green and Red dyes, respectively.
7. The percentage increase in total still productivity was 37.55, 29.02 and 20.48%, for the Black, Green and Red dyes solutions, respectively; compared to the reference still.
8. Percentage reduction of still productivity due to increasing water depth was 12.77, 8.95 and 9.17% for the Black, Green and Red dye solutions; when increasing water depth from 2 to 3 cm. The corresponding values were 16.86, 14.01 and 15.08% when increasing water depth from 3 to 4 cm, for the same sequence of dyes.
9. The percentage of desalinated water obtained in the last hour of the day is higher for higher depths of water.

Credit Authorship Contribution Statement

Aghareed M. Tayeb: Conceptualization, Review and editing, Investigation, Supervision.
Ashraf M. ElSaeed: Methodology, Investigation, Supervision.
Ali S. Mehany: Methodology, Writing original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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