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Evaluation quality of desalinated water derived from inclined copper-stepped solar still

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ABSTRACT

Nowadays, fresh drinking water has become increasingly scarce, especially in arid and semi-arid areas. Usually, the water found in these areas is seawater or brackish water and contains harmful contaminants, which directly affect human health, and therefore cannot be used for drinking purposes. Since arid and semi-arid areas are blessed with abundant solar radiation, small solar still units can be used to desalinate seawater and produce cheap drinking water. In this study, the capacity of an inclined copper-stepped solar still to produce fresh drinking water from seawater using solar energy was experimentally tested. This study aims to evaluate the distilled water quality produced by the solar desalination system. The system effectively eliminated all physicochemical parameters such as total suspended solids (TSS), pH, total dissolved solids (TDS), turbidity, salinity, conductivity, and atomic elements (Ca^{2+}, Cl^-, Mg^{2+}, Na^+, SO_4^{2-}, and K^+). Biological analyses were also conducted in this study including the analysis of ammoniacal nitrogen (NH_3–N), biological oxygen demand (BOD), and chemical oxygen demand (COD). Each parameter was found to have values that are within the safe limits set by the Malaysian NDWQS and WHO.

Keywords: Water desalination; Inclined stepped solar still; Drinking water quality; Solar energy; Malaysia NDWQS; WHO

1. Introduction

Drinking water is essential for sustaining human life. It is also the lifeblood of the industrial and agricultural sectors [1–3]. Drinking water shortages mainly occur due to population increase and a higher standard of living [4–6]. Freshwater and groundwater now makes up less than 0.5% of the earth's water and is gradually becoming depleted [7,8], while the remaining 97% is salt water and another 2% is located in the earth's polar region [9].

The lack of fresh drinking water is causing the spread of waterborne diseases in human populations [10,11]. Therefore, freshwater quality is very important and of the utmost concern. Water and energy are highly interconnected and interdependent [10,12]. Any action made in either area can greatly affect the other, whether negatively or positively. Therefore both water and energy govern the development of civilization [4].

Population increase—together with developments in the industrial and agricultural sectors as well as quality of life—has increased the need for more potable water [13]. Desalination of saline water is one of the key solutions to the potable water scarcity problem [14]. Desalination

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requires energy; it either utilizes the membrane processes (single-phase) or thermal process (phase-change) [12,15]Both processes increase fuel consumption. Hence, solar distillation is more promising and suitable compared to this method [16–18]. Höök et al. [19] observed increasing attention being placed on existing practices for water resource sustainability, as desalination plants are mostly commercial and depend on fossil fuel power or are driven from fossil fuel sources.

Therefore, the energy sources used is a significant issue, as it brings about side effects such as pollution, cost, and fuel shortage [20]. Hence, the main concern in remote regions is the discovery of new processes and resources to deliver cheap drinkable water via decentralized procedures [21]. Of all renewable energy sources, solar radiation has the greatest potential in rural and remote areas, especially in arid areas, so there is a huge potential for using solar energy to provide fresh water [22–26]. Therefore, solar desalination techniques can be implemented in small-scale units for arid and semi-arid areas [27]. Many researches have been carried out to increase the production rate of solar stills—from 2.5 to 5 l/m^2 d [28,29] using different techniques and designs via experiments [30–34] or mathematical modeling [35–39].These studies used hybrid solar stills, hemi-spherical stills, triangular pyramid-type solar stills, single basin double-slope stills, single-basin single slope stills, and pyramid-type solar stills [40].

In arid and semi-arid areas, people are facing a lack of drinking supply as well as low quality water such as brackish water with high concentrations of TDS, TSS, COD, and BOD. Besides that, the available water has an undesirable taste, color, and odor [41,42]. According to Malaysia's National Drinking Water Quality Standards (NDWQS) [43] and the World Health Organization (WHO) guidelines for drinking water [44], the quality of drinking water should match the mentioned standards of elements in order to protect the health of consumers.

Turbidity, conductivity, pH, total dissolved solids (TDS), and total suspended solids (TSS) are parameters that affect the quality of drinking water in high concentrations [45]. According to Bidgoli [46], WHO states that drinking water must be free of chemicals and microbial contaminations that have a direct effect on human health. This has prompted many studies to investigate drinking water quality all over the world [46,47].

This study aims to examine the performance of an inclined copper-stepped solar still in producing fresh drinking water via seawater desalination. A series of physicochemical and biological analyses were run on raw seawater and the distillate to estimate the quality of the distillate produced by the solar still.

2. Materials and methods

2.1. Metrological condition

The inclined copper-stepped solar still was developed in a car park in the new administration building of the Department of Civil and Structural Engineering, Faculty of Engineering and Built Environment, UKM, Bandar Baru Bangi, Selangor (latitude 2.939671°N and longitude 101.78784°E). The location of Kuala Lumpur and the location of Bangi (located around 35 km south of Kuala Lumpur) are shown in Fig. 1.

Fig. 1. Location of inclined copper-stepped solar still in UKM with respect to the Kuala Lumpur loacation. Source: https://www.google.com.my/maps.

The experiments were performed in 12 runs over 5-d stretches equivalent to a run of 12 h every day from 8:00 am till 7:00 pm for three months starting from 27th September 2016 until 23rd December 2016. The weather conditions and system temperatures were monitored and recorded on site on an hourly basis. Table 1 shows the statistical parameters of weather conditions and system temperature as well as the system productivity for the three months of experiments.

As shown in Table 1, the variation in ambient temperature during the inclined copper-stepped solar still operation time showed that the minimum and maximum ambient temperatures at the UKM site area were 23°C and 34°C, respectively. Furthermore, the variation in solar radiation was also recorded daily on an hourly basis and the minimum and maximum solar radiations were found to be 0.00 W/m² and 1032.75 W/m², respectively.

2.2. Inclined copper-stepped solar still system

Fig. 2 shows the schematic diagram of the inclined copper-stepped solar still used in this study. The system was designed so that the productivity of the inclined copper-stepped solar still could be assessed. The final dimensions of the inclined copper-stepped solar still included an interior design of 1.8 m in length, 1.2 m in width, and 0.20 m in height, along with 28 trays. The experimental setup consisted of two parts: the stepped solar still and the seawater feeding tank.

Table 1
Statistical parameters of weather condition and system temperatures at different points over the experiment periods

Statistical parameters	Solar radiation	Ta	Average wind velocity	Average humidity	Average cloud cover	T_o	T_i	$T_i - T_o$	T_v	T_w	T_t	Productivity
	W/m²	ºC	km/h	%	%	ºC						mL/unit area·h
Mean	413.48	29.42	8.68	73.86	82.87	41.39	46.09	4.70	48.96	47.60	47.57	399.55
Standard Error	12.75	0.09	0.17	0.41	0.41	0.39	0.51	0.14	0.55	0.52	0.52	13.21
Median	344.68	30.00	7.00	73.00	83.00	42.10	46.45	4.30	49.55	48.85	48.80	330.55
Mode	0.00	30.00	7.00	74.00	83.00	52.20	47.00	0.20	50.00	28.70	28.80	7.70
Stand. Dev.	341.99	2.43	4.49	10.99	10.87	10.49	13.60	3.70	14.66	13.94	14.02	354.48
Sample Vari.	116957.28	5.89	20.20	120.68	118.25	110.04	185.06	13.70	214.82	194.34	196.67	125654.18
Kurtosis	–1.22	–0.66	1.00	–0.58	7.36	–0.94	–0.98	–0.45	–0.93	–1.12	–1.12	–0.35
Skewness	0.41	–0.25	1.05	0.19	–1.41	–0.05	0.05	0.51	0.01	–0.11	–0.09	0.73
Range	1032.75	11.00	25.00	51.00	99.00	43.60	54.10	18.70	59.00	53.00	53.20	1436.60
Minimum	0.00	23.00	0.00	49.00	1.00	22.20	22.50	–2.60	22.90	23.50	23.50	2.20
Maximum	1032.75	34.00	25.00	100.00	100.00	65.80	76.60	16.10	81.90	76.50	76.70	1438.80
Sum	297702.56	21184.00	6247.00	53179.00	59667.00	29799.30	33182.60	3383.30	35254.50	34271.50	34251.90	287679.10
Count	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00	720.00

Where:
T_a = Ambient temperature
$T_i - T_o$ = inner temperature of condensing cover – outer temperature of condensing cover
T_V = Vapor temperature inside the solar still device
T_W = Temperature of basin water
T_t = Temperature of trays

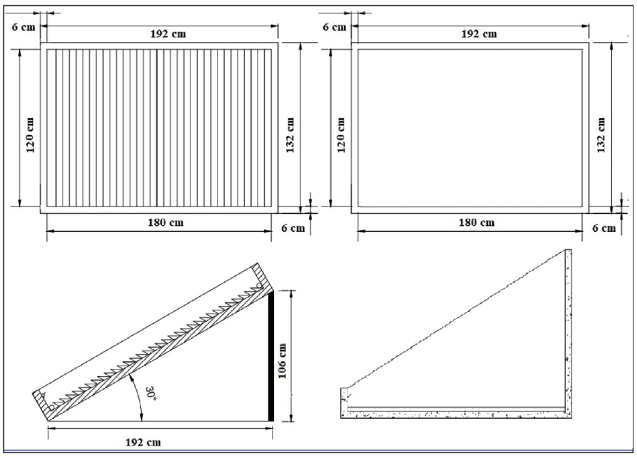

Fig. 2. Schematic diagram of the inclined copper-stepped solar still.

Here, the developed system was placed at an angle of thirty degrees to the horizontal, to enhance the condensing process and to encourage the water droplets to move faster and to directly flow to the trough channel. This is to minimize water droplet falls inside the still, as well as to get an inclined shape, as presented in Fig. 3.

The trays inside the system are made from copper. The tray cross-sections are illustrated in Fig. 4. These trays were placed inside a stainless steel box, where the bottom and sides were insulated using 6 cm thick sawdust.

A 25-liter plastic aspirator bottle was used to transfer seawater from Sepang Gold coast beach to the intake tank at the study area. Solar energy was utilized to heat up the seawater in the system; the produced water vapor formed condensate on the inner side of the condensing cover, and the water drops slipped along the cover. Then, the condensate was gathered in a stainless-steel container so that the water quantity could be measured later. The water inside the trays was controlled at a 3-m depth using an electric valve linked to a Finetek FD3002D mini single float.

Fig. 3. The developed inclined copper-stepped solar still with the main components.

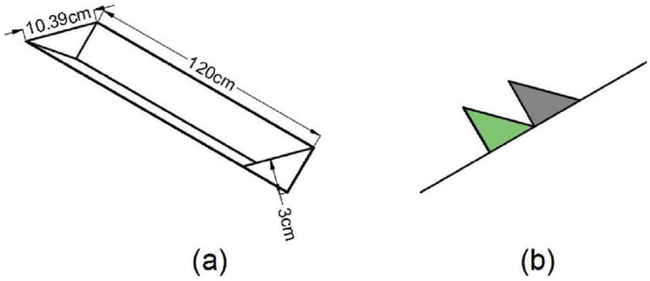

Fig. 4. A cross-sectional view of the copper trays dimensions inside the system and the vertical side of the steps.

3. Results and discussion

3.1. Distillate water productivity

During the experiments, the inclined copper-stepped solar still was activated for 24 h every day. The distillate production of the inclined copper-stepped solar still system was measured during the day and at night in the absence of solar radiation. The average nocturnal productivity of the solar still was 415.93 ± 174.45 ml/m^2 h.

Fig. 5 displays the daily and nocturnal yield of distilled water of the inclined copper-stepped solar still during the wet season, specifically on 19 October 2016. A high distillate production was observed once the hourly production of the inclined copper-stepped solar still reached maximum. Fig. 5 shows that the inclined copper-stepped solar still had some similar characteristics in which its production varied from day to day due to fluctuation in the temperature of its surroundings and the solar radiation ambient temperature. Moreover, the maximum daily production was 4383 mL/m^2 d, obtained on 19 October 2016 under a clear sky with little clouds. The productivity of this system relied on the

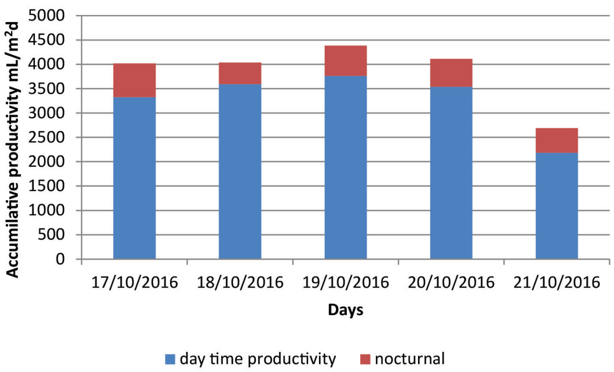

Fig. 5. Variation of the daily and nocturnal productivity of the inclined copper-stepped solar still for the 4th run.

Table 2
Raw seawater characteristics before being fed into the system

Run no.	pH	TDS mg/l	TSS mg/l	Turb. NTU	Cond. μS/cm	Salinity ppt	Cl^- mg/l	Na^+ mg/l	Mg^{2+} mg/l	SO_4^{2-} mg/l	Ca^{2+} mg/l	K^+ mg/l	BOD mg/l	NH_3-N mg/l
1	7.8	29270	653	36.2	48100	31.5	22461	10982	1120	2182	423	328	4.9	46
2	7.8	26900	687	37.51	48000	30.2	21554	10897	1043	2402	442	349	4.7	45
3	7.7	26070	694	39.4	46970	29.3	23826	11309	987	3064	494	367	4.6	41
4	7.8	29170	657	36.2	48100	31.5	19541	11951	822	2063	699	299	4.3	34
5	7.8	26970	647	37.51	48000	30.2	20572	11261	1136	2476	497	351	5.2	43
6	7.7	28070	684	39.4	45930	29.3	22382	10798	1244	2215	615	339	4.5	40
7	7.7	28170	673	36.1	48100	31.5	21054	10654	1334	2382	775	359	4.5	42
8	7.7	28170	673	36.1	48100	31.5	21054	10654	1334	2382	775	359	4.5	42
9	7.7	28170	673	36.1	48100	31.5	21054	10654	1334	2382	775	359	4.5	42
Average	7.8 ± 0.1	27884 ± 1058	671 ± 16	37 ± 1	4771 ± 762	31 ± 1	21499.7 ± 1245.5	11017.8 ± 429.5	1150.4 ± 179.3	2394.2 ± 283.4	610.6 ± 149.6	345.6 ± 21.1	5 ± 0.3	41.7 ± 3.40

intensity of solar radiation, so the nocturnal production only reached about 622 mL/m^2 d. Productivity of this system was greater than other inclined copper-stepped solar stills and conventional systems used worldwide [48–52].

3.2. Distillate water quality

The distillate quality of the system was determined via a series of laboratory analyses that determine the physicochemical results of the system including salinity, pH, total dissolved solids (TDS), total suspended solids (TSS), conductivity, turbidity and atomic elements (Cl^-, Ca^{2+}, Na^+, SO_4^{2-}, Mg^{2+}, K^+). Biological analyses results include biological oxygen demand, Heterotrophic Plate Counts (HPC), ammonia cal nitrogen (NH_3–N), and chemical oxygen demand, which are further compared with Malaysia's National Drinking Water Quality Standards. The raw seawater data and its average for this study are displayed in Table 2.

3.2.1. pH

pH is one of the most crucial parameters when measuring the quality of water. Water is considered acidic if it has a pH below 7.0 and alkaline if it has a pH above 7.0. The pH of water has no direct impact on human health however, alkaline water can cause water disinfection and acidic water can cause scale formation in metal pipes and plumbing systems [44]. The range of drinking water pH required by Malaysia's National Drinking Water Quality Standards [43] should be between 6.5 and 9.0. According to the World Health Organization (WHO) [44], the range should be between 6.5 and 8.5. As shown in Table 2, the pH of the seawater measured before it was fed into the inclined copper-stepped solar still was an average pH of 7.8 ± 0.10. On the other hand, the distilled water produced by this system yielded an average pH of 8.1 ± 0.10, which is in compliance with Malaysia's National Drinking Water Quality Standards. Fig. 6 presents the variations in pH during the period of operation of the solar still in comparison with Malaysia's National Drinking Water Quality Standards.

From Table 3 and Fig. 6, it can be seen that the pH of the distilled water increased with the increased operation

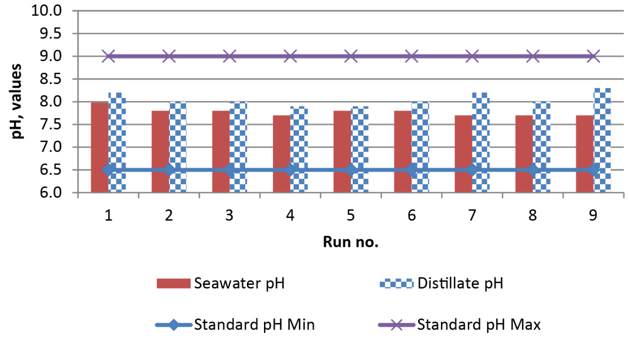

Fig. 6. Variation in the pH of raw seawater and distillate water with the Malaysia' National Water Quality Standard based on the experimental runs.

of the solar still functioning as a vaporizer utilizing natural energy; but not through boiling the water inside the still, in which the salts and microbes in the raw seawater would be left behind such as the water process during rain. This allows for natural pH buffering that produces excellent taste in the final product, unlike steam distillation. The increase in pH value is attributed to the TDS concentration in the distilled water [1].

3.2.2. Total dissolved solid (TDS)

Total dissolved solids (TDS) are particles usually smaller than 2 microns, which are present in the water column. TDS is also an important parameter in the evaluation of water quality. TDS shows the total content of all organic and inorganic matters found in the water [44]. The unit of measurement for TDS is milligrams per unit volume of water (mg/L). TDS is also sometimes noted as parts per million (ppm). The efficiency of the raw wastewater treatment of the solar still utilized in this study can be evaluated by calculating TDS. Therefore, the TDS values were calculated for raw seawater before and after it was fed into the inclined copper-stepped solar still.

Tables 2 and 3 display the results obtained from the laboratory test. It can be observed that the inclined copper-stepped solar still successfully removed 99.98% of TDS from the raw seawater. The TDS average value for raw seawater was 27884 ± 1058 mg/L, which was subsequently reduced to 7 ± 2 mg/L after going through the still. The range of TDS in drinking water, as mentioned in Malaysia's NDWQS and WHO, should be 1000 mg/L. The TDS obtained from the inclined copper-stepped solar still was below the maximum accepted limit of TDS concentration stated in Malaysia's National Drinking Water Quality Standards, as shown in Fig. 7.

The quality of distilled water obtained from the inclined copper-stepped solar still system is found to be safe for use as drinking water, as per Malaysia's NDWQS and WHO.

3.2.3. Total suspended solids (TSS)

Total suspended solids (TSS) refer to particles of inorganic materials, which are bigger than 2 microns. TSS is a significant parameter in water quality assessment. High concentrations of suspended solids may trigger many problems for aquatic life and health of streams.

The desalination capacity of the inclined copper-stepped solar still in this study was regulated by calculating the TSS concentration in raw seawater and later in the distilled water obtained from the still. In the solar still system, two main causes, which led to the removal of solid materials, were sedimentation and evaporation. In this way, the solids will not evaporate and will settle at the basin of the inclined copper-stepped solar still as residue.

Based on data obtained from the laboratory tests, as shown in Tables 2 and 3, 99.7% of TSS was successfully removed from the raw seawater using the inclined copper-stepped solar still in this study.

Fig. 8 displays the TSS average value of raw seawater, which is 671 ± 16 mg/L. Subsequently, the system purified the raw seawater so that its TSS average value was 2 ± 2

Table 3
Distillate seawater characteristics produced by the inclined copper-stepped solar still

Run no.	pH	TDS mg/L	TSS mg/L	Turb. NTU	Cond µS/cm	Salinity ppt	Cl^- mg/L	Na^+ mg/L	Mg^{2+} mg/L	SO_4^{2-} mg/L	Ca^{2+} mg/L	K^+ mg/L	BOD mg/L	NH_3-N mg/L
1	8.2	7.2	2	0.48	10.5	0	16.308	8.142	1.106	2.261	0.014	0.7	2.6	0.14
2	8	6.4	2	0.29	9.4	0	3.284	1.923	0.729	0.706	0.066	0.141	2.4	0.16
3	8	7.8	2	0.39	9.3	0	1.002	0.825	0.607	0.331	0.045	0.201	3.2	0.13
4	7.9	7.6	2	0.4	8.9	0	2.886	2.819	0.835	0.504	0.569	0.158	2.6	0.16
5	7.9	6.7	2	0.38	8.7	0	1.102	1.825	0.714	0.312	0.245	0.254	2.8	0.17
6	8	7.5	2	0.39	9.4	0	1.366	2.164	1.41	0.255	0.681	0.17	2.7	0.13
7	8.2	7.4	2	0.37	9.1	0	0.794	0.776	0.259	0.086	2.852	0.186	2.3	0.15
8	8	7.60	2	0.39	8.2	0	1.556	0.518	0.155	0.275	2.066	0.016	2.2	0.15
9	8.3	7.50	2	0.37	12.8	0	1.739	0.689	0.106	0.331	1.815	0.101	2.7	0.15
Average	8.10 ± 0.10	7.30 ± 2.00	2.00 ± 2.00	0.38 ± 0.00	10 ± 1.0	0.00 ± 0.00	3.34 ± 4.90	2.20 ± 2.40	0.70 ± 0.40	0.6 ± 0.7	0.93 ± 1.0	0.2 ± 0.2	3 ± 0.3	0.15 ± 0.0

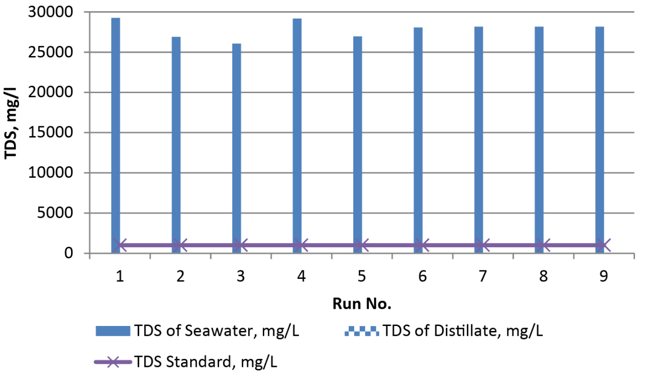

Fig. 7. Variation in TDS of the raw seawater and distillate of the inclined copper-stepped solar still in comparison with Malaysia's National Drinking Water Quality Standards.

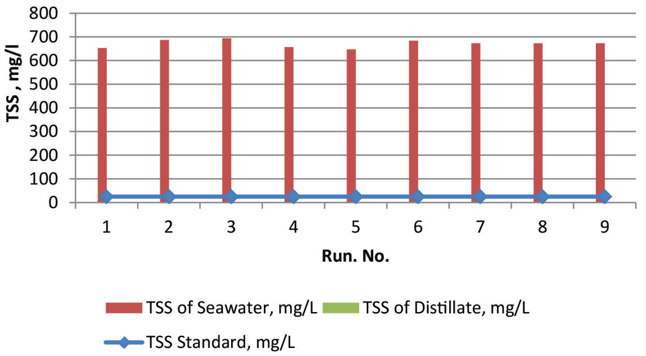

Fig. 8. Variation in the TSS of raw seawater and distillate for the inclined copper-stepped solar still in comparison to Malaysia's National Drinking Water Quality Standards.

mg/L. The range of TSS for drinking water mentioned in Malaysia's NDWQS is 25 mg/L.

In the meantime, the TSS obtained from the inclined copper-stepped solar still was below the maximum accepted limit of the TSS concentration range of Malaysia's NDWQS.

3.2.4. Salinity removal

Salinity measures all the salts that are dissolved in water. Salinity is referred to as parts per thousand (ppt). Normally, 85.7% of the salinity of water usually consists of two elements, namely Chlorine (Cl) and Sodium (Na). The remaining contents of seawater are Calcium (Ca), Potassium (K), Sulfate (SO_4^{2-}), and Magnesium (Mg). Thus, these elements—together with Sodium and Chlorine—constitute 99.4% of the salt in seawater [53]. The salinity of the raw seawater and distilled water obtained from the inclined copper-stepped solar still was measured and tested.

Based on the laboratory results shown in Tables 2 and 3, the salinity of the distilled water shows that the salinity removal efficiency of the inclined copper-stepped solar still was 100%. The average value of salinity for the raw seawater was 31 ± 1 ppt, which was then purified to 0 ± 0 ppt, as determined from the distilled water of the inclined copper-stepped solar still shown in Fig. 9.

The salinity range of drinking water according to Malaysia's NDWQS is 1%, which correlates to 1 ppt. The salinity of the distilled water produced by the inclined copper-stepped solar still was found to be below the maximum accepted level of salinity concentration set by Malaysia's NDWQS.

3.2.5. Electrical conductivity removal

Conductivity measures the capability of water to allow the flow of electricity. This function is directly controlled by the concentration of ions in the water [41]. The conductive ability of the ions is caused by dissolved salts and inorganic substances, for instance, sulfides, alkalis, chlorides, and carbon compounds. Higher water conductivity correlates to the presence of more ions while lower water conductivity shows that there are fewer ions present. Hence, the water is purer.

Based on data shown in Tables 2 and 3, the inclined copper-stepped solar still successfully eliminated 98.98% of the conductivity of raw seawater, which reflects the efficiency of the system in terms of water quality.

On the other hand, the average values of the raw sea water conductivity was 47711 ± 762 μS/cm before being purified to an average value of 10 ± 1 μS/cm, determined from the distilled water produced by the inclined copper-stepped solar still in this study, and as displayed in Fig. 10.

The conductivity values indicate the presence of dissolved solids in the distilled water. The electric conductivity of the distilled water produced by the inclined copper-stepped solar still was lower than the maximum accepted level (1000 μS/cm) for the range of conductivity values as per Malaysia's NWQS.

3.2.6. Turbidity removal

In assessing the quality of water, turbidity is a quantitative measure of the remaining un-dissolved elements. This factor is measured relatively using optical determination of water clarity. Turbidity is usually measured

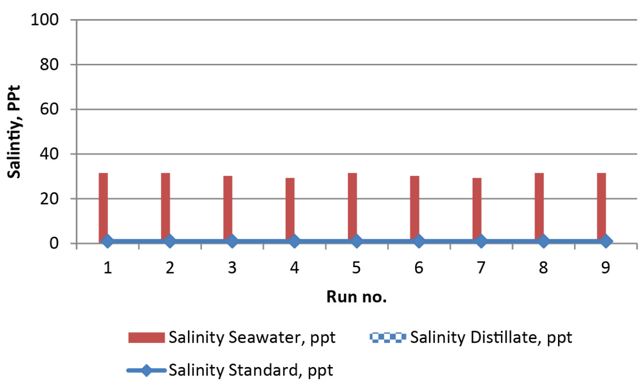

Fig. 9. Variation in the salinity of raw seawater and distillate for the inclined copper-stepped solar still in comparison with Malaysia's National Drinking Water Quality Standards.

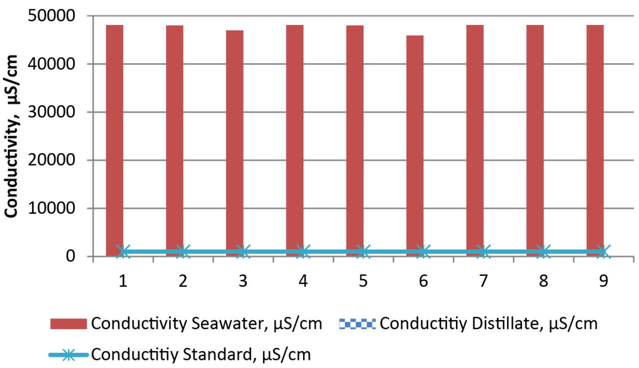

Fig. 10. Variation in the conductivity of the raw seawater and distillate of the inclined copper-stepped solar still in comparison with Malaysia's National Drinking Water Quality Standards.

in Nephelometric Turbidity Unit (NTU) [41]. Hence, the turbidity test is a good method to measure the efficiency of the solar still system used in this research. Based on data from the laboratory analysis displayed in Tables 2 and 3, the inclined copper-stepped solar still successfully removed 98.96% of turbidity in the raw seawater.

The raw seawater average value was 37 ± 1 NTU. It was then purified to an average value of 0.38 ± 0 NTU, as displayed in Tables 2 and 3. These values were obtained from the distilled water produced by the inclined copper-stepped solar still and shown in Fig. 11.

The presence of turbidity in the distilled water produced by the system is due to the presence of TDS in the water. Therefore, an increase in TDS also increases the turbidity of the water, and vice versa. The turbidity of drinking water based on Malaysia's NDWQS and WHO is 5 NTU. The salinity of the distillate produced by the inclined copper-stepped solar still in this study was found to be below the maximum accepted limit for turbidity as per Malaysia's NDWQS.

3.2.7. Atomic elements removal

Seawater on average is a combination of 96.5% pure water and 3.5% salt. Normally, 99% of salts in seawater consist of six elements, namely chloride (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), and sulfate (SO_4^{2-}) [53–56].

An atomic element test was done using an ion chromatography (IC) unit in the instrument laboratory of chemical engineering, Scholl, FKAM, UKM. Normally, the removal of salt elements is calculated in mg/L.

The efficiency of the inclined copper-stepped solar still can be evaluated by utilizing the laboratory data obtained for the raw seawater and distilled water from the inclined copper-stepped solar still, as displayed in Tables 2 and 3. Figs. 12–17 show the removal of atomic elements in the raw seawater achieved using the inclined copper-stepped solar still in this study, namely 99.98% Cl^-, 99.87% Ca^{2+}, 99.98% Na^+, 99.98% SO_4^{2-}, 99.94% Mg^{2+}, and 99.94% K^+.

On the other hand, the average concentration of atomic elements in the raw seawater was 21499.7 ± 1245.5 mg/L Cl^- purified to 3.34 ± 4.9 mg/L, 11017.8 ± 429.5 mg/L Na^+ purified to 2.2 ± 2.4 mg/L, 1150.4 ± 179.3mg/L Mg^{2+} purified to 0.7 ± 0.4 mg/L, 2394.2 ± 283.4 mg/L SO_4^{2-} purified to 0.6 ± 0.7mgL/l, 610.6 ± 149.6 mg/L Ca^{2+} purified to 0.9 ± 1.0 mg/L, and finally 345.6 ± 21.1 mg/LK^+ purified to 0.2 ± 0.2 mg/L.

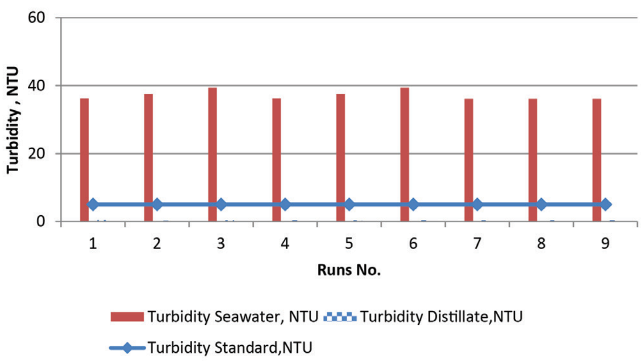

Fig. 11. Variation in the turbidity of raw seawater and distillate of the inclined copper-stepped solar still in comparison to Malaysia's National Drinking Water Quality Standards.

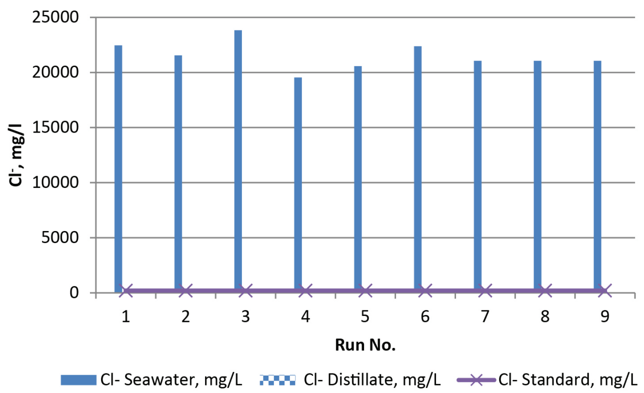

Fig. 12. Variation in the Cl^- elements of raw seawater, distillate, and National Drinking Water Quality Standards for Malaysia.

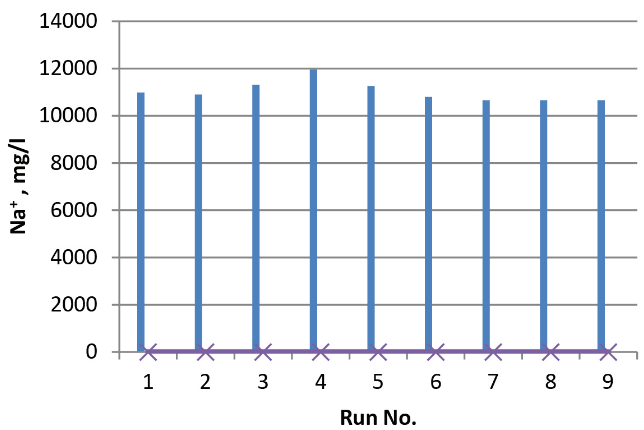

Fig. 13. Variation in the Na^+ elements in raw seawater, distillate, and National Drinking Water Quality Standards for Malaysia.

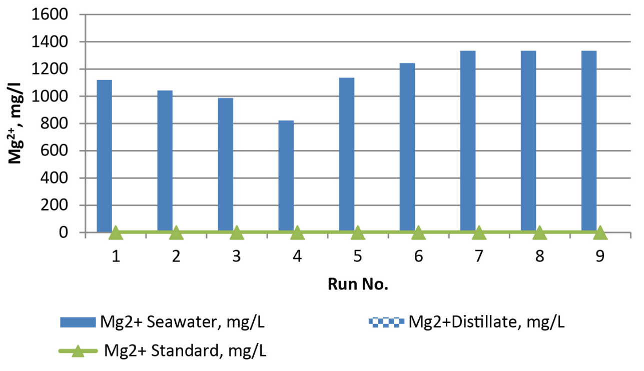

Fig. 14. Variation in the Mg^{2+} element in raw seawater, distillate, and National Drinking Water Quality Standards for Malaysia.

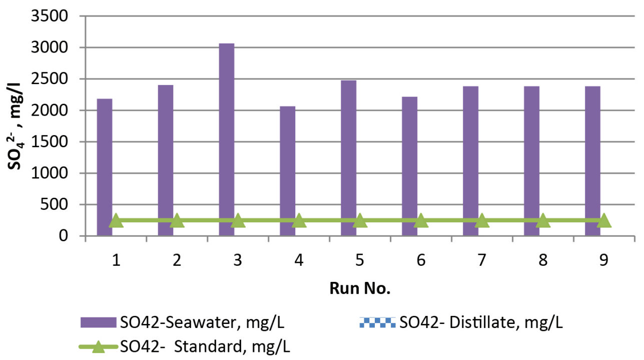

Fig. 15. Variation in the SO_4^{2-} element in raw seawater, distillate, and National Drinking Water Quality Standards for Malaysia.

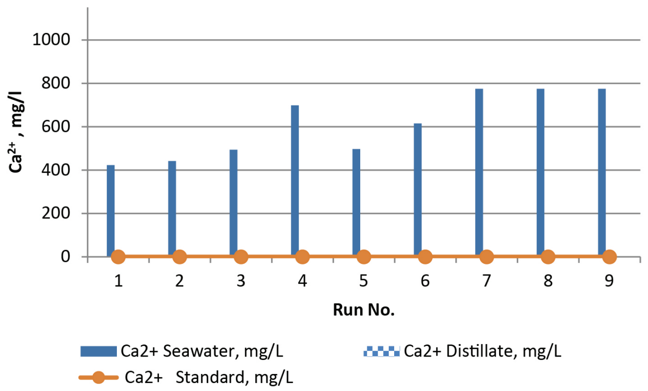

Fig. 16. Variation in the Ca^{2+} element in raw seawater, distillate, and National Drinking Water Quality Standards for Malaysia.

The atomic element concentration levels for drinking water, as stated in Malaysia's National Drinking Water Quality Standards, are 200 mg/L Cl^-, 250 mg/L SO_4^{2-}, 200 mg/L Na^+, – mg/L K^+. – mg/L Ca^{2+} and 150 mg/L Mg^{2+}. The salinity of the distilled water produced by the inclined copper-stepped solar still was lower than the maximum acceptance level of atomic element concentration range of Malaysia's NDWQS.

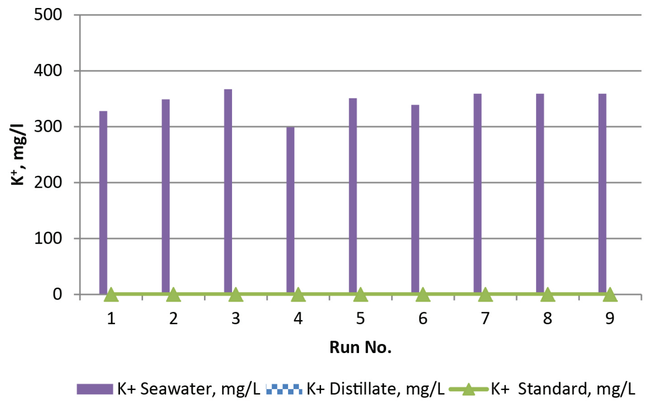

Fig. 17. Variation in the K+ element in raw seawater, distillate, and National Drinking Water Quality Standards for Malaysia.

3.2.8. Biological contaminant removals

3.2.8.1. Biochemical oxygen demand

Biochemical oxygen demand (BOD) is an index of the oxygen demand in water. BOD is a useful factor for evaluating the biodegradability of dissolved organic substances in water. In order to study the efficiency of the inclined copper-stepped solar still, the BOD of the raw seawater and distilled water fed into and produced by the inclined copper-stepped solar still, respectively, has to be analyzed.

The inclined copper-stepped solar still in this study showed a removal efficiency of BOD concentration in distilled water of up to 43.56%. In reference to Tables 2 and 3, the BOD average value of raw seawater was observed to be 5 ± 0.3 mg/L, which was then purified to 3 ± 0.3 mg/L, determined from the distilled water produced by the inclined copper-stepped solar still, as displayed in Fig. 18.

The BOD range for drinking water required by Malaysia's National Water Quality Standard is 6 mg/L. Hence, the BOD of the distillate obtained from the inclined copper-stepped solar still in this research is lower than the maximum level of BOD concentration range set by Malaysia's NDWQS.

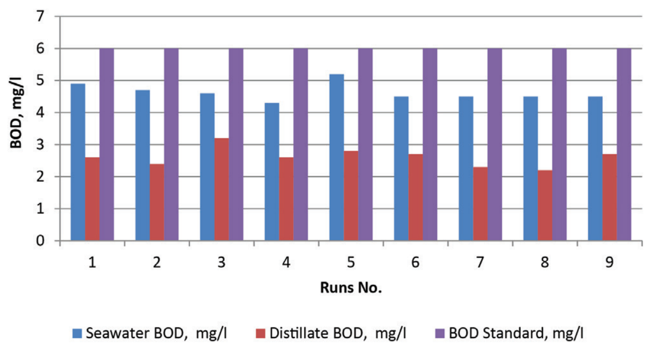

Fig. 18. Variation in the BOD of raw seawater and distillate of the inclined copper-stepped solar still in comparison with Malaysia's National Drinking Water Quality Standards.

3.2.8.2. Ammoniacal nitrogen removal

Ammoniacal nitrogen (NH_3–N) measures the ammonia content of water and is a measurement of the health of natural water. NH_3–N is commonly utilized in water purification systems. Ammonia is poisonous and can upset the equilibrium of a water system. NH_3–N in water is referred to in mg/L.

Hence, in order to examine the quality of distilled water obtained from the inclined copper-stepped solar still, the NH_3–N of the raw seawater and distillate was tested and compared with Malaysia's NDWQS, as outlined in Tables 2 and 3.

Based on the laboratory results presented in Table 2 and 3, 99.6% NH_3–N removal efficiency was successfully achieved, as determined from the distilled water of the inclined copper-stepped solar still. The NH_3–N average value of the raw seawater was 41.7 ± 3.4 mg/L, which was then purified to 0.15 ± 0.0 mg/L, from analyzing the distilled water produced by the inclined copper-stepped solar still presented in Fig. 19.

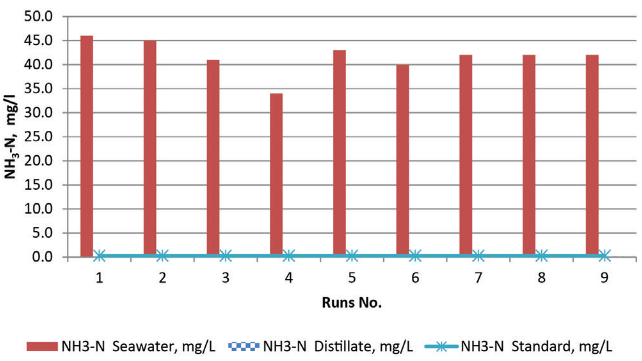

Fig. 19. Variation in NH3-N of the raw seawater and distillate of the inclined copper-stepped solar still in comparison with Malaysia's National Drinking Water Quality Standards.

The NH_3–N range for drinking water, as mentioned in Malaysia's NDWQS, is 0.3 mg/L. The NH_3–N of the distilled water of the inclined copper-stepped solar still in this research was lower than the maximum accepted level of NH_3–N concentration range of Malaysia's NDWQS.

3.2.9. Comparison with other works

The quality of drinking water is a sign of a developed and healthy community. Seawater desalination plants are a main source of drinking water in many arid and semi-arid areas in the world. The quality of distilled water from these systems is very important for ensuring the health of the next generation. A comparison of distilled water from this study and other studies is presented in Table 4.

It can be observed from Table 4 that the inclined copper-stepped solar still of this study shows a higher percentage efficiency in purifying seawater to distilled water in comparison with other R.O. Systems across all parameters. Fig. 20 shows the distilled water quality enhancement as a result of using the inclined copper-stepped solar still in this study in comparison with other R.O. systems.

As shown in Fig. 20, the system in this study resulted in a higher efficiency of water purification in comparison to other R.O. systems. This could be due to the water evaporating and leaving behind contaminants as settlements, resulting in only pure water droplets finally reaching the trough channel in the system in this study.

Table 4
Comparison of distillate quality of other research works with the present work

Parameters	Present work			RO [42]			RO [57]		
	Seawater	Distilled	Removal, %	Brackish water	Distilled	Removal, %	Seawater	Distilled	Removal, %
pH	7.7	8.1	NA	7.82	6.42	NA	7.9	6.9	NA
TDS, mg/l	27884.4	8.1	99.97	2610	159	93.91	37749	1233	96.73
TSS, mg/l	671.2	2	99.70	NA	NA	NA	NA	NA	NA
Turb. NTU	37.2	0.4	98.92	NA	NA	NA	9.3	0.2	97.85
Cond. µS/cm	47711.1	9.6	99.98	4130	251	93.92	58075	1953	96.64
Salinity ppt	30.7	0	100.00	NA	NA	NA	NA	NA	NA
Cl^-, mg/l	21499.8	3.3	99.98	800	77	90.38	22020	710	96.78
Na^+, mg/l	11017.8	2.2	99.98	550	58	89.45	9715	436	95.51
Mg^{2+}, mg/l	1150.4	0.7	99.94	124	9.5	92.34	1581	31	98.04
SO_4^{2-}, mg/l	2394.2	0.6	99.97	790	46.4	94.13	3067	58	98.11
Ca^{2+}, mg/l	610.6	0.9	99.85	166	7.7	95.36	416	7.7	98.15
K^+, mg/l	345.6	0.2	99.94	10	2.42	75.80	588	14.6	97.52
BOD, mg/l	4.6	2.6	43.48	NA	NA	NA	NA	NA	NA
NH_3-N, mg/l	41.7	0.1	99.76	NA	NA	NA	NA	NA	NA

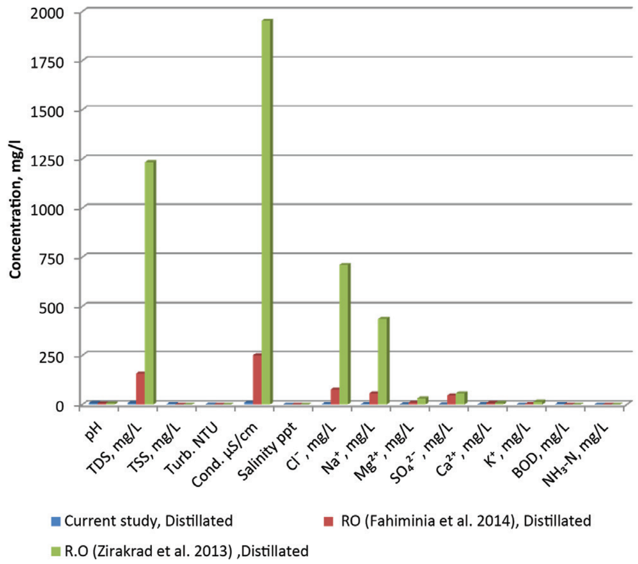

Fig. 20. Comparison of distillate quality of other research works with the present work.

4. Conclusion

This study aimed to investigate the possibility of using an inclined copper-stepped solar still to produce potable drinking water via seawater desalination utilizing solar energy. The system was run for 3 months starting from 27th September to 23rd December 2016. The system studied in this research has proven hugely successful in producing fresh drinking water in accordance with WHO standards and Malaysia's NDWQS. The system productivity almost reached 4.4 l/m^2 d. The inclined copper-stepped solar still was efficient in removing physicochemical and biological contaminations, where it produced distilled water free from 99.98% TDS, 99.7% TSS, 100% salinity, 99.98% electrical conductivity, 98.96% turbidity, 99.98% Cl^-, 99.98% Na^+, 99.94% Mg^{2+}, 99.98% SO_4^{2-}, 99.87% Ca^{2+}, and 99.94% K^+, 43.56% BOD, and 99.6% NH_3–N.

References

[1] V. Sivakumar, E. Ganapathy Sundaram, Experimental studies on quality of desalinated water derived from single slope passive solar still, Desal. Water Treat., 57 (2016) 1–11.
[2] A.A. El-Sebaii, E. El-Bialy, Advanced designs of solar desalination systems: A review, Renew. Sustain. Energy Rev., 49 (2015) 1198–1212.
[3] P.N. Kumar, A.M. Manokar, B. Madhu, A.E. Kabeel, T. Arunkumar, H. Panchal, R. Sathyamurthy, Experimental investigation on the effect of water mass in triangular pyramid solar still integrated to inclined solar still, Groundw. Sustain. Dev., 5 (2017) 229–234.
[4] T. Chen, Q. Wang, Y. Qin, X. Chen, X. Yang, W. Lou, M. Zhou, G. He, K. Lu, Knowledge, attitudes and practice of desalinated water among professionals in health and water departments in Shengsi, China: A Qualitative Study, PLoS One., 10 (2015) e0118360.
[5] M. Qasim, N.a. Darwish, S. Sarp, N. Hilal, Water desalination by forward (direct) osmosis phenomenon: A comprehensive review, Desalination, 374 (2015) 47–69.
[6] M.S.S. Abujazar, S. Fatihah, A.R. Rakmi, M.Z. Shahrom, The effects of design parameters on productivity performance of a solar still for seawater desalination: A review, Desalination, 385 (2016) 178–193.
[7] S. Gorjian, B. Ghobadian, Solar desalination: A sustainable solution to water crisis in Iran, Renew. Sustain. Energy Rev., 48 (2015) 571–584.
[8] A.D. Khawaji, I.K. Kutubkhanah, J.M. Wie, Advances in seawater desalination technologies, Desalination, 221 (2008) 47–69.
[9] K. Vinoth Kumar, R. Kasturi Bai, Performance study on solar still with enhanced condensation, Desalination, 230 (2008) 51–61.
[10] E. Deniz, Energy and exergy analysis of flat plate solar collector-assisted active solar distillation system, Desal. Water Treat., 57 (2016) 1–9.
[11] M. Appadurai, V. Velmurugan, Performance analysis of fin type solar still integrated with fin type mini solar pond, Sustain. Energy Technol. Assessments, 9 (2015) 30–36.
[12] R. Cipollone, A. Cinocca, P. Talebbeydokhti, Integration between concentrated solar power plant and desalination, Desal. Water Treat., 57 (2016) 28086–28099.
[13] M.S.S. Abujazar, S. Fatihah, A.E. Kabeel, Seawater desalination using inclined stepped solar still with copper trays in a wet tropical climate, Desalination, 423 (2017) 141–148.
[14] L. Zeng, M. Du, X. Wang, A thermodynamical approach for evaluating energy consumption of the forward osmosis process using various draw solutes, Water, 9 (2017) 1–17.
[15] R. Zarasvand, F. Suja, F. Tarkian, F. Mashhoon, S. Rahimi, A. Atash, Solar desalination of Gas Refinery wastewater using membrane distillation process, DES., 291 (2012) 56–64.
[16] M.S.S. Abujazar, S. Fatihah, I.A. Ibrahim, A.E. Kabeel, S. Sharil, Productivity modelling of a developed inclined stepped solar still system based on actual performance and using a cascaded forward neural network model, J. Clean. Prod., 170 (2017) 147–159.
[17] S. Maiti, C. Bhatt, P. Patel, P.K. Ghosh, Practical and sustainable household seawater desalination using an improved solar still, Desal. Water Treat., 57 (2016) 3358–3371.
[18] A. El-Bahi, D. Inan, Analysis of a parallel double glass solar still with separate condenser, Renew. Energy, 17 (1999) 509–521.
[19] M. Höök, R. Hirsch, K. Aleklett, Giant oil field decline rates and their influence on world oil production, Energy Policy, 37 (2009) 2262–2272.
[20] S. Burn, M. Hoang, D. Zarzo, F. Olewniak, E. Campos, B. Bolto, O. Barron, Desalination techniques: A review of the opportunities for desalination in agriculture, Desalination, 364 (2015) 2–16.
[21] M.S.S. Abujazar, S. Fatihah, E.R. Lotfy, A.E. Kabeel, S. Sharil, Performance evaluation of inclined copper-stepped solar still in a wet tropical climate, Desalination, 425 (2018) 94–103.
[22] H. Mousa, A.H. Al-Muhtaseb, M. Abu-Arabi, Improving the productivity of a falling film solar desalination unit, Desal. Water Treat., 57 (2016) 9602–9608.
[23] R.Z. Asadi, F. Suja, F. Mashhoon, S. Rahimi, Feasibility studies for using a solar still on Sarkhon Gas Refinery wastewater recovery, Desal. Water Treat., 30 (2011) 154–160.
[24] R. Zarasvand Asadi, F. Suja, M.H. Ruslan, N.A. Jalil, The application of a solar still in domestic and industrial wastewater treatment, Sol. Energy, 93 (2013) 63–71.
[25] M.T. Chaibi, An overview of solar desalination for domestic and agriculture water needs in remote arid areas, Desalination, 127 (2000) 119–133.
[26] A.F. Mashaly, A.A. Alazba, Neural network approach for predicting solar still production using agricultural drainage as a feedwater source, Desal. Water Treat., 57 (2016) 28646–28660.
[27] R. Poblete, G. Salihoglu, N. Kamil Salihoglu, Investigation of the factors influencing the efficiency of a solar still combined with a solar collector, Desal. Water Treat., 57 (2016) 29082–29091.
[28] A.E. Kabeel, Z.M. Omara, M.M. Younes, Techniques used to improve the performance of the stepped solar still: A review, Renew. Sustain. Energy Rev., 46 (2015) 178–188.

[29] V. Velmurugan, K. Srithar, Performance analysis of solar stills based on various factors affecting the productivity: A review, Renew. Sustain. Energy Rev., 15 (2011) 1294–1304.
[30] A.A. AL-Karaghouli, W.E. Alnaser, Experimental comparative study of the performances of single and double basin solar stills, Appl. Energy., 77 (2004) 317–325.
[31] B.A. Akash, M.S. Mohsen, W. Nayfeh, Experimental study of the basin type solar still under local climate conditions, Energy Convers. Manag., 41 (2000) 883–890.
[32] F.F. Tabrizi, A.Z. Sharak, Experimental study of an integrated basin solar still with a sandy heat reservoir, Desalination, 253 (2010) 195–199.
[33] O.O. Badran, Experimental study of the enhancement parameters on a single slope solar still productivity, Desalination, 209 (2007) 136–143.
[34] S.J.P. Gnanaraj, S. Ramachandran, D.S. Christopher, Enhancing the productivity of double-slope single-basin solar still with internal and external modifications, Int. J. Ambient Energy, (2017) 1–6. doi:10.1080/01430750.2017.1340338.
[35] S. Nijmeh, S. Odeh, B. Akash, Experimental and theoretical study of a single-basin solar sill in Jordan, Int. Commun. Heat Mass Transf., 32 (2005) 565–572.
[36] V. Velmurugan, S. Pandiarajan, P. Guruparan, L.H. Subramanian, C.D. Prabaharan, K. Srithar, Integrated performance of stepped and single basin solar stills with mini solar pond, Desalination, 249 (2009) 902–909.
[37] D. Kumar, Prashant Kumar, Mathematical Modeling of Conventional Solar Still Coupled With Solar Air Heater, IJISET – Int. J. Innov. Sci. Eng. Technol., 1 (2014) 379.
[38] Y.H. Zurigat, M.K. Abu-Arabi, Modelling and performance analysis of a regenerative solar desalination unit, Appl. Therm. Eng., 24 (2004) 1061–1072.
[39] S.K. Shukla, V.P.S. Sorayan, Thermal modeling of solar stills: An experimental validation, Renew. Energy, 30 (2005) 683–699.
[40] S. Vala, H. Panchal, B. Kanabar, Comparative performance evaluation of single-slope and pyramid-shaped solar stills: experimental evaluation, Int. J. Ambient Energy, (2017) 1–8. doi: 10.1080/01430750.2017.1345012.
[41] N. Rahmanian, S.H.B. Ali, M. Homayoonfard, N.J. Ali, M. Rehan, Y. Sadef, A.S. Nizami, Analysis of physiochemical parameters to evaluate the drinking water quality in the state of perak, Malaysia, J. Chem., (2015). doi:10.1155/2015/716125.
[42] M. Fahiminia, M. Mosaferi, R.A. Taadi, M. Pourakbar, Evaluation of point-of-use drinking water treatment systems' performance and problems, Desal. Water Treat., 52 (2014) 1855–1864.
[43] N. Ministry of Health Malaysia, National Drinking Water Quality Standard, 2nd ed., 2004.
[44] H.G. Gorchev, G. Ozolins, WHO guidelines for drinking-water quality, 2011.
[45] W. Jia, C. Li, K. Qin, L. Liu, Testing and analysis of drinking water quality in the rural areas of high-tech district in Tai'an City, J. Agric. Sci., 2 (2010) p155.
[46] H.N. Bidgoli, Chemical analysis of drinking water of Kashan District , Central Iran, World Appl. Sci. J., 16 (2012) 799–805.
[47] S. Shah, N. Mistry, I.H. Jujara, N. Tiwari, Design and construction of solar water distillation system, IJSRSET., 3 (2017) 606–610.
[48] V. Velmurugan, K.J. Naveen Kumar, T. Noorul Haq, K. Srithar, Performance analysis in stepped solar still for effluent desalination, Energy., 34 (2009) 1179–1186.
[49] Z.M. Omara, A.E. Kabeel, M.M. Younes, Enhancing the stepped solar still performance using internal and external reflectors, Energy Convers. Manag., 78 (2014) 876–881.
[50] A.A. El-Sebaii, S.J. Yaghmour, F.S. Al-Hazmi, A.S. Faidah, F.M. Al-Marzouki, A.A. Al-Ghamdi, Active single basin solar still with a sensible storage medium, Desalination, 249 (2009) 699–706.
[51] T. Arunkumar, K. Vinothkumar, A. Ahsan, R. Jayaprakash, S. Kumar, Experimental study on various solar still designs, ISRN Renew. Energy., 2012 (2012) 1–10.
[52] O.O. Badran, H.A. Al-Tahaineh, The effect of coupling a flat-plate collector on the solar still productivity, Desalination., 183 (2005) 137–142.
[53] M.J. Pidwirny, Fundamentals of Physical Geography, 2nd ed., 2006.
[54] S.A. Kalogirou, Seawater desalination using renewable energy sources, Prog. Energy Combust. Sci., 31 (2005) 242–281.
[55] A.M.K. El-Ghonemy, Water desalination systems powered by renewable energy sources: Review, Renew. Sustain. Energy Rev., 16 (2012) 1537–1556.
[56] S. Gorjian, B. Ghobadian, T. Tavakkoli Hashjin, A. Banakar, Experimental performance evaluation of a stand-alone point-focus parabolic solar still, Desalination, 352 (2014) 1–17.
[57] A. Zirakrad, S.J. Hashemian, M.T. Ghaneian, Performance study of reverse osmosis plants for water desalination in Bandar-Lengeh, Iran, J. Community Heal. Res., 2 (2013) 8–14.