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Charcoal characterization and application is solar evaporator for seawater desalination

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Abstract. Solar desalination is the most attractive and simple technique for desalination process but suffers low thermal efficiency. The objective of this research is to study the effect of charcoal in seawater desalination for clean water production. The experiment was conducted in a basin type solar evaporator by using seawater with charcoal to seawater mass ratio variation of 1:50 to 1:500. The investigation was carried out for eight hours in sunny daylight. The water qualities including pH, conductivity, total dissolve solid (TDS), chemical oxygen demand (COD) and turbidity of the seawater and amount of evaporated water were determined. The spent and fresh charcoals were also characterized by using Nitrogen Adsorption (BET), X Ray Detector (XRD) and Scanning Electromagnetic Microscope (SEM). It is found that the addition of charcoal in the water leads to20 % increment of water temperature. Charcoal's exposed area to the energy source significantly affects the temperature raise. The best charcoal to water mass ratio was achieved at 1:100 to produce 16.8% evaporated water. Charcoal was stable in seawater because minimum changes of pore size and pore volume were observed. In conclusion, charcoal is a potential salt adsorbent and medium for solar thermal energy storage for seawater solar desalination process.

1. Introduction

Desalination process is commonly used to obtain fresh water from seawater, brackish water and contaminated water. Fresh water is necessary for human to survive, to boost industry and for food sustainability activities via agriculture. Fresh water from river, lakes and ponds sufficiently became scare due to massive industrial growth, population, chemical pollution and harmful organism. Due to that, several common desalination processes like Reverse Osmosis (RO), Multi-Stage Flash (MSF), Multi-Effect Distillation (MED), and Electrodialysis are applied to treat saline or brackish water. This process required conventional energy source like fossil or electricity [1]. Common desalination process like distillation is difficult to implement in remote area due to unavailable of conventional energy and very costly. Renewable solar energy is green energy source with various applications. High intensity of solar energy in the countries, like Malaysia and Saudi Arabia, make desalination via solar is effectively applicable to convert saline and brackish water into fresh water.

Solar evaporator, also known as solar still, is most widely used in small scale desalination process. Solar distillation process basically replicates the way nature purifies water via evaporation and condensation processes. The sun's energy is used to heat up and elevate water temperature to increase the evaporation rate. Even though the heating process will not go up to boiling point, the temperature rise is enough to make water vapour deposited on the glass surface of solar still where condensation process takes placed and form fresh water. However, disadvantage of solar still is low productivity because it strongly depends on season, region, intensity of solar radiation and sunshine time interval during that day [2]. Arunkumar et al. [3] claim that there were two reasons for low productivity of solar still. Firstly, the rejection on latent heat of condensation to the atmosphere is difficult and secondly, the difficulty of rising the evaporation temperature and decreasing the condensation temperature. Therefore, many researchers keep on attempts to improve design of solar still in order to enhance the production of fresh water.

Productivity of fresh water by solar still strongly depends on the intensity of solar radiation and number of sunshine hour during that day. Because of this limitation, several innovation technique such as integrated external air-cooled condenser [4], utilizing the heat waste from other process and feed into solar still system [5], adding flat solar collector [6] and utilization of inverted absorber [7] have been made to improve the productivity and boost the output of fresh water as compare to conventional solar still. Parameter affecting solar still productivity such as water depth, inclination cover, internal reflector, external reflector and application of absorbing material are also studied to improve the production of fresh water [8-10]. Thermal storage material became promising solution because it helps to improve the heat and mass transfer of solar still. It also helps to overcome difference between energy supply and energy demand that causes by variability variation of solar radiation that causes energy losses during experiment, and thus enhance distillation efficiency. Materials like gravels [11-12], metallic wire sponges [13], dye [14] and many more are used in solar stills which increase the water temperature in the solar still and remain for longer time. It is because the materials absorb and store the thermal energy from sun that causes water to have longer warm environment.

Many researchers agree that more fresh water production is achieved when thermal storage material is added in the solar still. The material provides higher surface area for thermal absorption that leads to increase the evaporation rate [15]. Nafey et al., [11] who used black gravel is a solar still that equipped with black rubber sheets managed to achieve 3.5 kg/m2 daily yield and improve the productivity by 19%. Meanwhile, about 60% of water was produced when black volcanic rock was used in the solar still [13]. Interestingly, Shanmuga & Mahadi [14] found that black dye is able to increase 65% of evaporated water. Materials like black granite gravels, pebbles, blue metal stones and paraffin wax was tested by Arjunan et al. [12]. They found that the black granite gravels are more effective than pebbles, blue metal, stone and paraffin wax materials which produced higher evaporated water than other materials. The gravels effectively increased 10% of solar still efficiency than conventional still. Charcoal that derived from wood has high energy absorptivity and high porosity. This creates larger surface for radiative and convective heat transfer [16]. Okeke et al. [17] claim that by adding charcoal to the water, it increases the energy supplied for evaporation by increasing the solar energy absorption the water. Mahdi et al. [18] also report that charcoal is a good material for absorber/evaporator and water transport medium.

In this paper, the investigation to characterize and evaluate the potential of charcoal as a salt adsorbent and solar energy absorbent in the seawater solar desalination. The effect of charcoal to seawater mass ratio was studied.

2. Methodology

2.1. Materials

The seawater was obtained at Teluk Cempedak beach (Latitude: 3.815 Longitude: 103.363) in Malaysia The sample was kept in the fridge at 4 °C to maintain the sample quality. The charcoal was obtained from gasification of wood at 600 °C.

2.2. Characterizations

The CHNOS of the charcoal was determined by using Vario Macro CHNO elemental analyser. The surface characteristic of fresh and spent charcoal was analysed by using Thermo-Scientific Surfer. The

BET Multipoint technique was employed. A nitrogen gas was used as the adsorbate. The sample was degassed in vacuum at 150 °C for 12 hours prior to analysis. The XRD diffraction was performed using the Rigaku Miniflex II to investigate the charcoal crystalline phase. The samples were irradiated by Nickel filtered Cu Kα with a wavelength (λ) of 1.542 A at 40 mA and 45 kV, and scanning ˚ from 10° to 80° at 4°.min-1. The crystallite size was determined via the Scherrer Equation (cf. Equation 1).

$$D_p(Particle\ diamter) = \frac{0.90\ \times\lambda}{\beta cos\theta} \qquad (1)$$

where, β is the line broadening at half of the maximum intensity while θ is the Bragg angle. The surface morphologies of the charcoal were evaluated via field emission JEOL JSM-7800F, Japan scanning electron microscope (SEM). The charcoal powder was mounted on specimen stubs with double-sided adhesive carbon tapes. The specimen was coated with platinum and was examined at 1e3 kV with various magnifications.

2.3. Solar still desalination procedure

The investigation was carried out in a single type basin solar still evaporator that was fabricated from prospect plastic with three mm thickness. The evaporator specification is illustrated in figure 1. The size of the based evaporator basin was 0.4 m x 0.45 m. The cover of the evaporator was inclined at 30°. Mirrors were installed in every side inside the basin to increase the light intensity to water. A two mm of plywood was used at the base of the basin to decrease the heat loss during the experiment. Collection trough was placed at the end of the cover to collect the condensate.

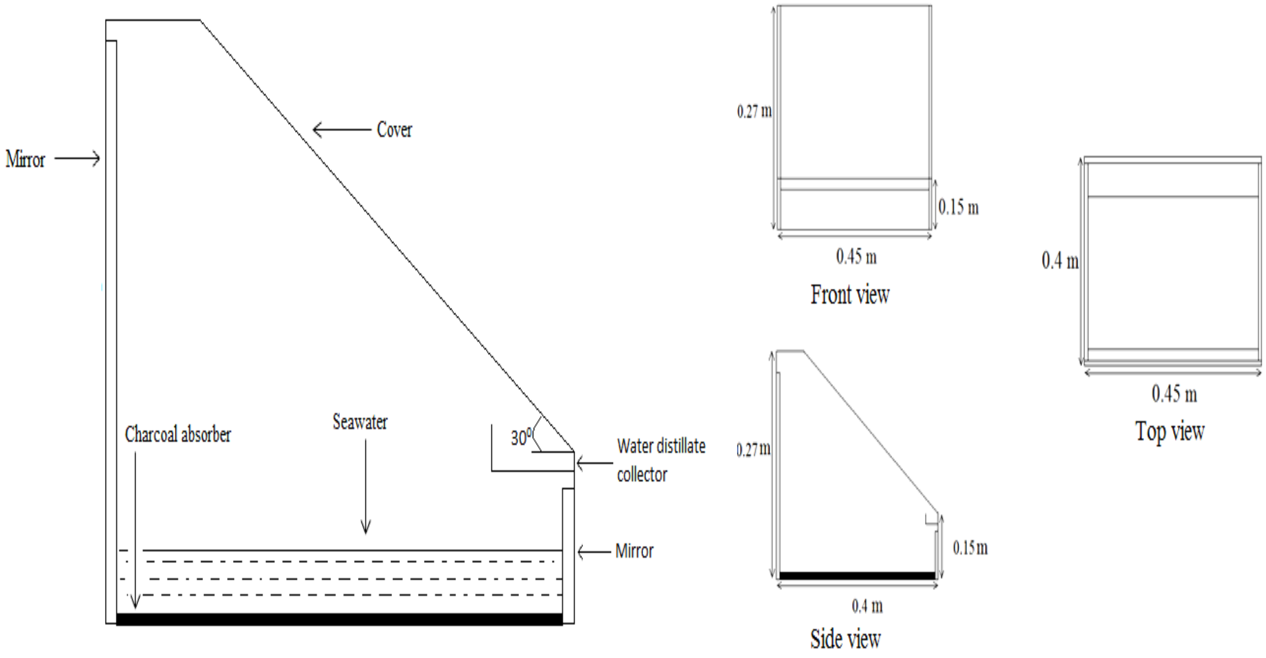

Figure 1. Schematic diagram and dimension of solar still evaporator.

Experiment was conducted by using three litre of seawater and poured into the basin with charcoal to water mass ratio was in a range of 1:50, 1:100 and 1:500. The set up was then placed at open area under sunny daylight for seven hour from 10.00 a.m. to 5.00 p.m. The temperature of seawater inside the basin was recorded. The fresh seawater, spent seawater and evaporated product were analysed to determine the pH, conductivity, total dissolve solid, COD, BOD and turbidity

2.4. Water analysis

The seawater (before and after the investigation) and the evaporated water were analysed to determine the pH, conductivity, total dissolve solid (TDS), chemical oxygen demand (COD), and turbidity. The pH value, conductivity and TDS were measured by using Hach SensION+ Conductivity Meter Kit (EC5 5060 model). Turbidity of seawater and evaporated water was measured by using Turbidity Meter (Hach 2100Q). In COD analysis, COD Digestion Reagent Vial High Range (435 COD HR) is used to test the amount of organic compound in seawater (before and after the investigation) and evaporated water. The water sample was diluted and placed in the COD Digestion Reagent Vial and then preheated in COD reactor for two hours. After two hours, the vial was placed in the Hach (DRB 200) to measure the COD value.

3. Result and discussion

3.1. Charcoal characterization

The fresh and spent charcoals are also characterised to determine the charcoal's surface area structure and morphology. The charcoal CHNOS is also determined. The charcoal surface characterization was done by using BET while the charcoal surface morphology was carried out using SEM. The charcoal elemental composition of CHNOS is tabulated in table 1. It clearly indicates that the main composition of the charcoal is carbon (75.84 wt%). Oxygen, O is determined by difference, contributes to 15.8 wt% in the charcoal. Pastor-Villegas et al. [19] also claimed that the carbon and oxygen content in wood charcoal from kiln is 74 wt% and 17 wt% respectively. Less than 5 wt% of hydrogen and nitrogen content was obtained in the charcoal. It also can be seen that the sulphur, S content is very low (0.93 wt%). This also indicates that the charcoal is considered as a green charcoal to be used in combustion.

Table 1. Elemental composition of charcoal.

Sample	C (wt%)	H (wt%)	N (wt%)	S (wt%)	O* (wt%)
Charcoal	75.84	2.47	4.96	0.93	15.80

*determined by difference

The surface characterization by using BET for fresh and spent charcoals is presented in table 2. Generally, less than 3 % changes of pore size can be observed for all samples. The pore size of the charcoal was in range of 376.7 to 387.5 μm. The pore size of the charcoal decreased slightly from 387.5 μm to 380.1 μm after testing when charcoal to water mass ratio was at 1:100. The more charcoal was added into the water, the more pore size reduction can be observed. The pore volume of the charcoal, on the other hand, indicates that the pore volume of the spent charcoal was slightly increased. The increment of the pore volume is recorded from 0.035 cm^3g^{-1} to a maximum of 0.046 cm^3g^{-1}after testing. In Pehlivan et al., [20] study of charcoal pore characteristic from different wood, they found that the pore volume of the charcoal was in the range of 0.47 till 1.1 cm^3g^{-1}. This is caused by the different amounts of tarry matter or products of decomposition formed during the wood carbonization processes that deposited in the pore. The tarry matter or product of decomposition during the wood carbonization processes might be dissolved during the investigation. That might be the reason why larger pore volume in the spent charcoal is observed. It can be deduced that the charcoal is stable for seawater desalination.

Table 2. Charcoal pore structure.

Sample	Testing condition Charcoal to water mass ratio	Pore Size (μm)	Pore Volume (cm^3g^{-1})
Fresh charcoal		387.5	0.035
Spent charcoal	1:50	382.2	0.040
Spent charcoal	1:100	380.1	0.045
Spent charcoal	1:500	376.7	0.046

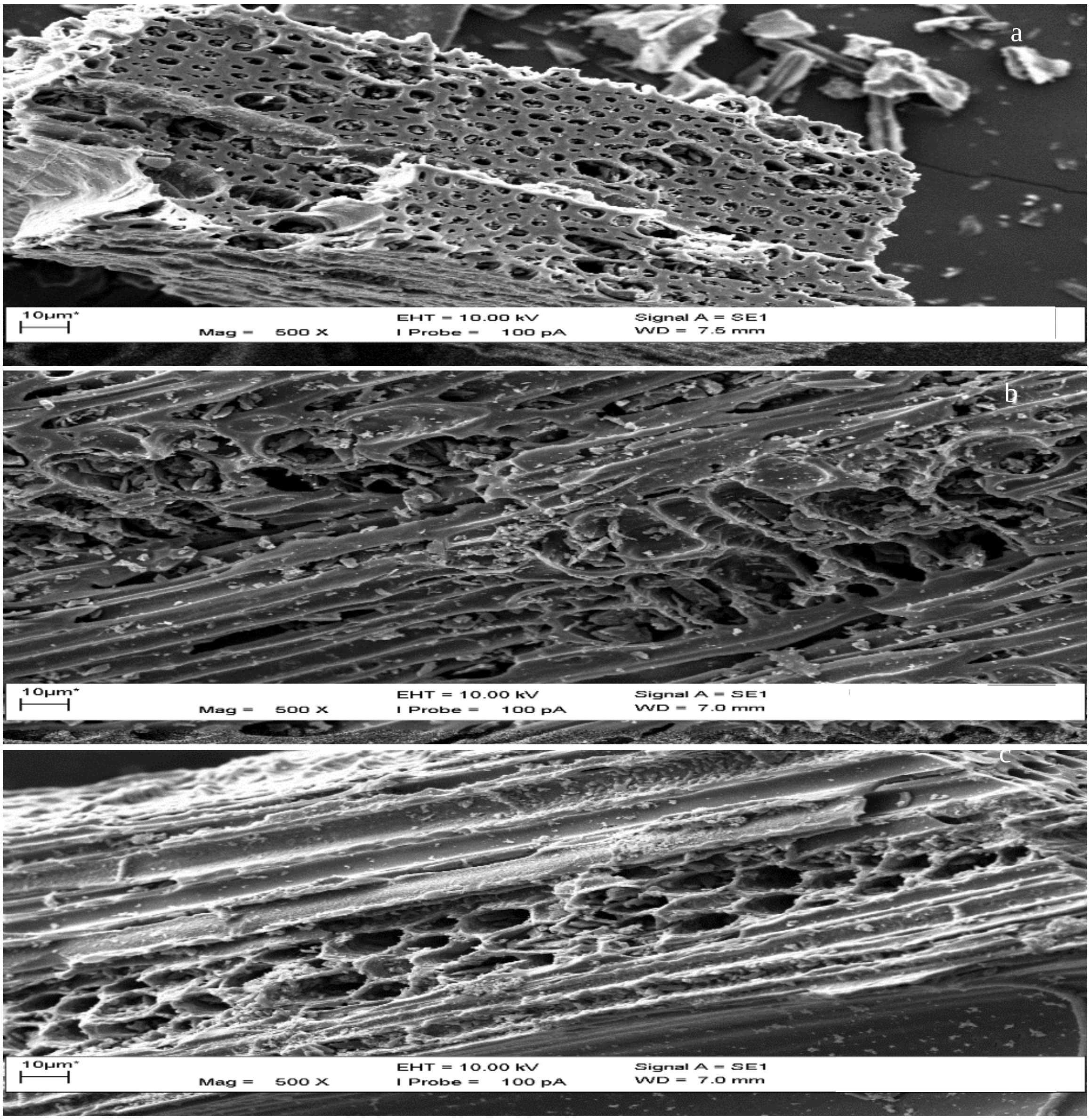

Figure 2. SEM images at 500x magnification of (a) fresh charcoal, (b) spent charcoal at 1:100 (c) spent charcoal at 1:500.

The charcoal morphology of fresh and spent charcoal that tested with charcoal to water mass ratio of 1:100 and 1:500 are presented in figure 2. It can be seen that fresh charcoal has macro pores structure

(Refer figure 2a). Charcoal is a porous carbon material, with a heterogeneous surface and a disorganized pore structure susceptible of change by adequate thermal treatments to be used as adsorbent [20]. Charcoal typically is derived from wood. Wood is a polymeric structure consisting of carbohydrates (cellulose and hemicellulose) and lignin, with small amounts of extraneous organic chemicals [20]. The pore structure of spent charcoal after tested at charcoal to water mass ratio of 1:100 and 1:500 were slightly enlarge which affect the pore volume of the charcoal (Refer table 2). Moreover, small crystals can be observed on the spent charcoal structure (Refer figure 2b and 2c) which might be caused by the deposition of the salt on the spent charcoal. Although the pore volume of the charcoal structure is slightly increased, the structure of spent charcoal is still intact. This indicates that the charcoal is stable in the water after tested for seven hours. Although water adsorbed in micropores structure of charcoal [19], this stable pore structure in the charcoal is necessary to be a good absorbent in seawater desalination.

The fresh and spent charcoals that tested at charcoal to water mass ratio of 1:100 were also characterized using X-ray diffraction (XRD) to analyse the crystal structure on the charcoal. The analysis result is illustrated in figure 3. The carbon peak at 2ϴ of 25.38, 42.96 and 47.47 was achieved indicating the existence of carbon in the charcoal. In addition, the present of salt, NaCl peaks at 2ϴ of 33.10, 46.10 and 78.32 were also obtained on the surface of spent charcoal. These also explain that the present of small white crystals that deposited on the spent charcoal (Refer figure 2b and 2c). It demonstrates that the charcoal's capability to act as salt absorbent for seawater desalination.

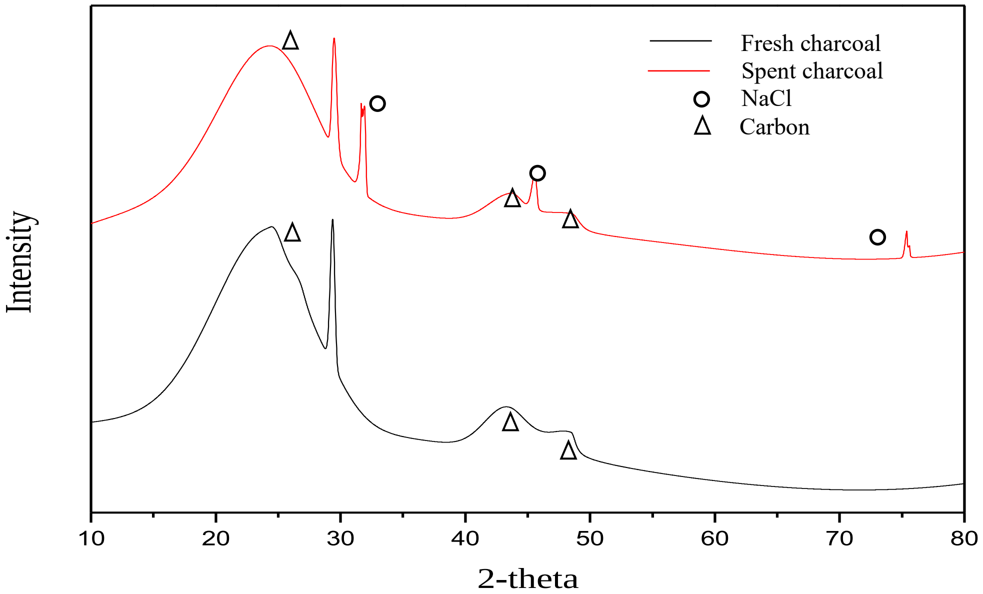

Figure 3. XRD analysis for fresh and spent charcoal.

3.2. Effect of charcoal addition on water temperature

The investigation was conducted in the solar still evaporator with different charcoal to seawater mass ratio. The charcoal to water mass ratio was set at 0:1, 1:50, 1:100 and 1:500. The water temperature was recorded every hour and the result is illustrated in Fig 4. It clearly can be seen that the addition of charcoal significantly increased the water temperature. Maximum water temperature can be observed at 1300 till 1500 hours for all conditions. The water temperature increased from 23 °C to 50 °C when no charcoal was used. However, the highest water temperature, which rose up to 60 °C from 27 °C, was achieved when the charcoal to water mass ratio was at 1:100. Although the highest amount of charcoal was used at charcoal to water mass ratio at 1:50, highest water temperature at 57 °C was obtained. About similar water temperature (56 °C) was also obtained when charcoal to water mass ratio was at 1:500. It can be seen that the amount of charcoal in the water does not affect the water temperature. Regardless the amount of charcoal, the expose area of the charcoal to sunlight during the investigation was similar. Therefore, it is believed that the charcoal surface area that exposed to sun light during the investigation significantly influence the water temperature.

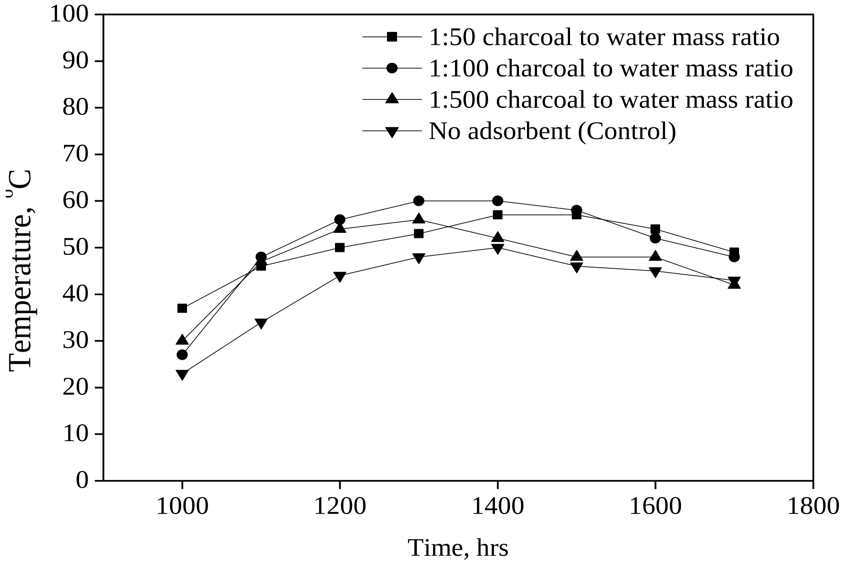

Figure 4. Temperature profile of seawater when charcoal is added.

However, the amount of charcoal in the water affected the temperature profile after 1600 hours. It can be seen that the water temperature was at 49 °C when charcoal to water mass ratio of 1:50. Meanwhile, 42 °C of water was obtained when the charcoal to water mass ratio was at 1:500. It clearly indicates that the charcoal is able to store the energy from water to maintain the water temperature. This is because charcoal has ability to enhance the absorption of solar radiation and act as heat storage material [21]. Thus, charcoal also can enhance the water temperature and increase the evaporation rate of the seawater.

3.3. Hybrid seawater desalination with charcoal adsorbent

The result of water analysis and evaporated water that produce in solar still is tabulated in table 3. The result clearly indicates that only 6.87 % of evaporated water was obtained when charcoal was not used. Small different can be observed when no charcoal was added. However, significant change was achieved when charcoal was added into water during investigation. Higher evaporated water yield was achieved 16.8% when charcoal to water mass ratio was at 1:100. Meanwhile, 14.5 % and 12.7% of evaporated water were obtained when the charcoal to water mass ratio were at 1:50 and 1:500 respectively. The production of evaporated water is significantly influenced by the water temperature. Increasing the water temperature leads to increase the evaporated water production. The highest water temperature and evaporated water yield was achieved when charcoal to water mass ratio was at 1:100. In contrast, the lowest evaporated water yield and water temperature were obtained when the charcoal to water mass ratio was at 1:500. This is because charcoal is able to absorb the solar radiation and increase the water temperature [21], which causes more evaporated water to produce. Tiris et al. [22] also observed similar result when charcoal was used to increase the evaporation rate by increasing the water temperature.

Table 3. Produced water yield and characterization.

	Fresh Seawater	No adsorbent (control)	Charcoal ratio 1:50	Charcoal ratio 1:100	Charcoal ratio 1:500
Conductivity, mS/cm	51.60	54.30	55.50	56.50	55.90
pH	7.93	8.06	8.27	8.22	8.19
TDS, g/L	33.10	34.70	35.50	36.20	35.80
COD reduction, %		0	55.00	60.20	62.70
Turbidity reduction, %		0	44.70	27.70	27.10
Evaporated water, g		206.15	447.15	511.72	380.65
Yield, wt. %		6.87	14.70	16.80	12.50

The spent water of the investigation was also characterized. The conductivity of the water indicates the salinity of the water. It clearly can be observed that the salinity of water (salt content in the water) increased as more evaporated water was produced. For instance, the salinity of water was obtained at 56.5 mS.cm^{-1} when the charcoal to water mass ratio was set at 1:100 that yield 16.8 % evaporated water. A small increment was observed on the pH value of the spent seawater. The total dissolved solid (TDS) also shares the same pattern as the pH value. There is a small increment of pH and TDS when no charcoal was used. This was caused by the increase of contaminant in the water due to evaporation process. It is also can be observed that the more charcoal content in the water, the pH value and the TDS increased. For example, the pH increased from 7.93 to 8.27 when the charcoal to water mass ratio was set at 1:50. The TDS value increased from 33.1 to 35.5 g.L^{-1}at the same condition. The increment of the pH value might be caused by the charcoal composition. Charcoal contains of 71.3 % of fixed carbon, 5 % of ash and 23% of volatile matter [23]. The major components of charcoal is carbon (73 – 90 %) and oxygen (5-17%) [19]. The ash of the charcoal typically rich in CaO and alumina [19, 24-25]. That is the reason why the pH value increased when charcoal was used in solar evaporation.

Interestingly, as higher amount of charcoal was used, higher turbidity reduction was achieved. About 44.6 % of turbidity reduction was achieved when charcoal to water mass ratio was set at 1:50. Meanwhile, similar turbidity reduction for water was observed when charcoal to water mass ratio was at 1:100 and 1:500. The COD value reduction reduced as more charcoal was added. The highest COD value was obtained at 62 % when the charcoal to water mass ratio was set at 1:500. Carbon typically used as an adsorbent [19], due to their non-polar nature, which adsorb selectively non-polar rather than polar substances. However, the oxygen content has an effect on the adsorbent–adsorbate interactions and in the resulting adsorptive properties [23]. That might be the reason why less effective of COD reduction can be achieved when charcoal to water mass ratio was at 1:50 compared to charcoal to water mass ratio of 1:500.

Table 4 tabulates the evaporated water characteristic that produced at different charcoal to water mass ratio. All evaporated water is very clean and fresh water with pH value of 6.98 till 7.76. The COD value and TDS of waters are less than one. The turbidity of the waters are also less than 1.50 NTU. This character is complied with WHO drinking water standard. Thus, it can be deduced that the solar still desalination are able to produce drinking water and treat the polluted water effectively. Thus, it can be deduced that the water production via solar still desalination is clean and drinkable. This technology is necessary to overcome water sarcasm.

Table 4. Evaporated water analysis

	No adsorbent (control)	Charcoal ratio 1:50	Charcoal ratio 1:100	Charcoal ratio 1:500	Drinking water quality (WHO) [26]
pH	7.76	6.98	7.01	7.76	6.5-8
Conductivity, mS/cm	0.89	0.64	0.59	0.71	1
TDS, g/L	0.57	0.74	0.39	0.91	1
Turbidity, NTU	1.20	1.14	1.02	1.50	5

4. Conclusion

Solar desalination is the cheapest and most green technology for clean water production. The effect of charcoal addition in seawater solar still desalination was investigated. Charcoal is cheap, has thermal capacity and a good absorbent for impurities removal in water. The addition of charcoal leads to significantly increase the temperature of the seawater that resulted to increase the evaporation rate. Charcoal exposure area to the energy source plays significant role to the raise of water temperature. The charcoal is also able to absorb impurities as more than 60% of COD reduction was observed and stable for seawater solar desalination. More than 15% of evaporated water with drinking water standard was obtained via charcoal solar desalination. It can be deduced that the addition of charcoal enhances the water temperature, evaporation rate and pollutants degradation in the water.

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