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Investigation on the Urban Grey Water Treatment Using a Cost-Effective Solar Distillation Still

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Abstract: Treating urban grey water with physical, chemical, and biological treatment techniques and reusing it as a sustainable non-potable water source has received much attention recently, yet there is a lack of studies regarding it. In this work, a typical slum nearby an urban household area in Malaysia was selected as a source of contaminated grey water which is located on the opposite side of a building site (100°29′ E and 5°7′ N) located in an urban area in a city in the Perak state, namely Parit Buntar, where the total urban grey water was being accumulated. Poor sanitation of that slum was seen to pose various health risks to the public, and hence, the importance of treating its grey water was perceived. Thus, this study was conducted to evaluate the performance of a low-cost double slope passive solar still by treating the grey water from the aforementioned slum, as well as to analyze the quality, quantity, and cost per liter of the produced water. Grey water was collected and filled in the solar still basin at s depth of 1 cm. The cover and basin of the solar still were made from transparent polythene film and black-painted stainless steel trough, respectively, while the frame was made from polyvinyl chloride (PVC), and the solar still was named PSSG1 abbreviated. PSSG1 was exposed to Malaysia's climate conditions for several days from 8.00 a.m. to 6.00 p.m. at Universiti Sains Malaysia (USM), which was able to produce the maximum amount of water up to 4.11 L/m^2·d with the cost per liter/m^2 of only USD 0.0082. Water quality parameters tested showed that water produced from PSSG1 met the standards of the restricted and unrestricted reusable non-potable grey water, the World Health Organization (WHO), and the Malaysian class I drinking water standards. It was also found that the PSSG1 with higher average daily basin water temperature produced water with higher quality for the reuse applications and yielded healthier water compared to the water produced by some reported previous grey water treatment techniques. Therefore, the cost-effective PSSG1 can be used as a daily practical alternative for treating low-strength grey water collected from various urban household areas in Malaysia in order to assist pollutants removal from the drained urban grey waters.

Keywords: grey water reuse; triangular-shaped solar distiller; polythene film cover; economical potable water production

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1. Introduction

The urban wastewater consisting of all non-toilet streams originating from kitchen sinks, dishwashers, baths, hand basins, and washing machines is generally referred to as urban grey water [1–4]. A total of 50–70% of each household's total wastewater is grey water [5,6]. Reusable treated grey water reuses as sustainable non-potable water has received great attention recently due to having low contaminants [7]. Until now, in the urban zones in many developing countries, the volume of contaminated grey water from slums due to the kitchen, laundry, and bathing activities in many household areas has increased due to the high rates of urbanization and population growth. Poor accessibility and the lack of legal compliance in many urban slums have caused poor sanitation leading to the increase in the occurrence of diseases and environmental pollution and consequently poses various health risks to the public. The quality parameters of grey water by different categories of the bathroom, laundry, kitchen, and mixed grey water are shown in Table 1 [8].

Table 1. The quality parameters of grey water by different categories [8].

	Bathroom	Laundry	Kitchen	Mixed
pH(-)	6.4–8.1	7.1–10	5.9–7.4	6.3–8.1
TSS (mg/L)	7–505	68–465	134–1300	25–183
Turbidity (NTU)	44–375	50–444	298.0	29–375
COD (mg/L)	100–633	231–2950	26–2050	100–700
BOD (mg/L)	50–300	48–472	536–1460	47–466
TN (mg/L)	3.6–19.4	1.1–40.3	11.4–74	1.7–34.3
TP (mg/L)	0.11- > 48.8	ND- > 171	2.9- > 74	0.11–22.8
Total coliforms (CFU/100 mL)	10–2.4 × 10^7	200.5–7 × 10^5	>2.4 × 10^8	56–8.03 × 10^3
Fecal coliforms (CFU/100 mL)	0–3.4 × 10^5	50–1.4 × 10^3	-	0.1–1.5 × 10^8

The quality parameters of different categories of grey water, as analyzed by Li (2009), indicated that the kitchen and the laundry grey water had higher organics and physical pollutants compared to the bathroom and mixed grey water [8]. The results also showed that the bathroom and laundry grey water were less contaminated by microorganisms compared to the other grey water streams. Based on this study [8], bathroom and mixed grey water were classified as low-strength grey water, while grey water from laundry and kitchen basins were considered as medium- and high-strength grey water, respectively. Therefore, treating grey water is one of the main challenges in protecting the environment and human health through reuse water applications [9,10]. Grey water treatment aims to provide non-potable water for reuse applications such as laundry, toilet flushing, windows and car washing, lawn irrigation, fire extinguishing, and groundwater discharge [1,3]. The reusable grey water needs to achieve four quality standards, namely, sanitary safety, aesthetics, environmental acceptance, and financial feasibility standards after the reuse treatment processes [11]. As stated in several pieces of research [11–14], the guideline for non-potable grey water reuse as developed by Li et al. in 2009 [15] for the unrestricted and restricted water reuse encompasses the parameters of pH, fecal coliform, total coliforms, total suspended solids (TSS), biochemical oxygen demand (BOD_5), total nitrogen (TN), turbidity, and total phosphorous (TP) [15]. According to the guideline [15], the unrestricted reuse of grey water for non-potable water purposes, such as recreational impoundments, lakes, and ponds with body contact (swimming purpose), requires a high range of water quality parameters as follows: pH: 6–9, fecal coliform: $\leq$10/mL, total coliforms: $\leq$100/mL, TSS: $\leq$30 mg/L, BOD_5: $\leq$10 mg/L, TN: $\leq$1.0 mg/L, TP: $\leq$0.05 mg/L and turbidity: $\leq$2 NTU.

Many studies have been conducted about the treatment of urban households with grey water at low, medium, and high strength levels using different techniques, such as physical, chemical, and biological systems, in order to produce non-potable water for reuse applications based on the above guideline. Some researchers investigated the physical treatments of household grey water such as using the nylon sock type filter followed by the steps of sedimentation and disinfection [16], a slanted soil filter [17], a sand filter along with the activated carbon and disinfection [18], a medium strength UF membrane [19], a submerged spiral wound module [20], ultrafiltration (UF) membrane of 0.05 µm pore size [21], a direct nano-filtration membrane [22], sand filtration combined with the membrane filtration and disinfection [23] and micro and ultrafiltration membranes [24]. Low strength bath grey water was treated by March et al. [16] in which the quality parameters of COD, turbidity, the suspended solids (SS), and TN were reduced from 171 mg/L, 20 NTU, 44 mg/L and 11.4 mg/L in the influent to 78 mg/L, 16.5 NTU, and 18.6 mg/L and 7.1 mg/L in the effluent, respectively. In another study by Itayama et al. [17], the COD, the BOD, the SS, the TN, and the TP in the kitchen basin grey water were reduced from 271 mg/L, 477 mg/L, 105 mg/L, 20.7 mg/L, and 3.8 mg/L to 40.6 mg/L, 81 mg/L, 23 mg/L, 4.4 mg/L, and 0.6 mg/L, respectively, using a slanted soil filter. The chemical treatments of grey water were studied in a few studies, such as the use of an electro-coagulation process followed by a disinfection stage [25], the application of coagulation systems with the magnetic ion exchange resin process, and the coagulation process using aluminum salt [26] as well as application of photocatalytic ozonation [27]. Several studies investigated the performances of several biological treatment techniques such as rotating biological contractor (RBC), sequencing batch reactor (SBR), anaerobic sludge blanket (UASB), constructed wetland (CW), and membrane bioreactors (MBR)) in order to treat medium- and high-strength grey water. For example, Nolde [11], Friedler et al. [28], and Eriksson et al. [29] investigated the performance of the RBC, while Shin et al. [30] and Hernandez et al. [31] studied the performance of the SBR in the grey water treatment. Meanwhile, Hernandez et al. [31] and Elmitwalli and Otterpohl [32] looked into the performance of UASB, and Li et al. [7] and Gross et al. [33] focused on the use of CW as the biological treatment process. The performance of MBR for the treatment was investigated by Lesjean and Gnirss [34], Liu et al. [35], Merz et al. [36], Ding et al. [37,38], Atanasova et al. [39], Bani-Melhem et al. [40] and Fountoulakis et al. [41]. The performance of SBR followed by ultrafiltration was studied by Kaminska and Marszalek [42], Chrispim, and Nolasco evaluated the performance of biofilm reactors [43], practicing a hybrid MBR in comparison with a conventional MBR was studied by Palmarin and Young [44], the use of stacked multi-layer reactors with passive aeration and particle trapping was investigated by [45] for the treatment of grey water.

In work by March et al. [16], the physical process was performed in which the removal rates of some parameters, such as COD, BOD_5, turbidity, TSS, TN, and TP from the bath grey water were reported as 54.38% (not available) N/A, 17.50%, 57.72%, 37.71%, and N/A, respectively. Meanwhile, Itayama et al. [17], who also examined the physical process, reported the removal values as 85.01%, 83.01%, N/A, 78.09%, 78.74%, and 84.21% from the kitchen basin grey water. In another experiment by Lin et al. [25] using the chemical treatment, the results were observed at 60%, 60.86%, 90.69%, 68.96%, N/A, and N/A, respectively. Meanwhile, Pidou et al. [26], who applied the chemical treatment, reported the removal values as 63.71%, 88.78%, 90.81%, N/A, 12.77%, and 94.57%, respectively. Using the RBC as a biological treatment, Friedler et al. [28] identified the removal values as 70.88%, 88.81%, 94.24%, 62.79%, 69.68% and 58.33%, respectively (Table 2).

Table 2. The calculated pollutants removal rates from grey water using several physical, chemical, and biological treatment techniques in previous studies.

Authors and Year [Ref.]	Type of Treatment	Removal Rate (%) of					
		COD	BOD_5	Turbidity	TSS	TN	TP
(March et al., 2004) [16]	Physical	54.38	N/A	17.50	57.72	37.71	N/A
(Itayama et al., 2004) [17]	Physical	85.01	83.01	N/A	78.09	78.74	84.21
(Lin et al., 2005) [25]	Chemical	60.00	60.86	90.69	68.96	N/A	N/A
(Pidou et al., 2008) [26]	Chemical	63.71	88.78	90.81	N/A	12.77	94.57
(Friedler et al., 2005) [28]	Biological	70.88	88.81	94.24	62.79	69.68	58.33

The above studies identified that the physical treatment systems alone were not adequate to ensure an acceptable range of impurities decreased from the urban grey water [15]. Although, the chemical treatments of low-strength grey water were capable of removing the pollutants originating from organic materials, suspended solids, and surfactants well. However, it was reported that employing the chemical methods is not appropriate for the treatment of medium- and high-strength urban grey water [15]. Reportedly, the best approaches to grey water treatment were identified as using the integration of aerobic biological methods such as RBC, SBR, and CW with physical filtration and disinfection [15]. Meanwhile, MBR is considered the greatest feasible treatment alternative [6,46] in order to supply non-potable reusable grey water. However, it seems that the above treatment systems alone are not capable of producing reusable grey water that meets the World Health Organization (WHO) drinking water standards. In contrast, solar desalination stills were reported as one of the cost-effective alternatives to treat contaminated water in order to produce safe and freshwater [47–63] without employing the solid–liquid separation stage in the pre-treatment system, including the septic tank and screen and filter bags, in order to decrease the number of particles, thus investigating the solar still performance in term of households urban grey water treatment and comparing its performance with the performances of each of the reported physical, chemical, and biological treatment system seems obligatory.

Solar still is a sealed container with different configurations of shapes, i.e., triangular [47–55], trapezoidal [56–60], pyramid [61], tubular [62], and hemispherical [63], in which it is mainly encompassed of basin/bed to keep the contaminated water and has a transparent cover to allow the solar radiation intensities pass through it and thus to heat the basin water.

In a solar still, the evaporation and condensation processes between the basin surface water and the inner cover of the solar still (the basic process of the hydrological cycle) would occur to produce fresh distilled water [64,65] (Figure 1). The rate of condensed water vapor droplets on the inner surface of the transparent cover of a solar still (glass cover) strongly depends on the rate of water evaporated from the surface of the basin water in the solar still in the form of vapors (Figure 1). The following equations and formulas are presented with the calculations of the rates of condensed vapor droplets based on the basin water evaporation in which the condensation and evaporation rates greatly depend on the values of temperature of basin water and glass of the solar still [51,52,64–68].

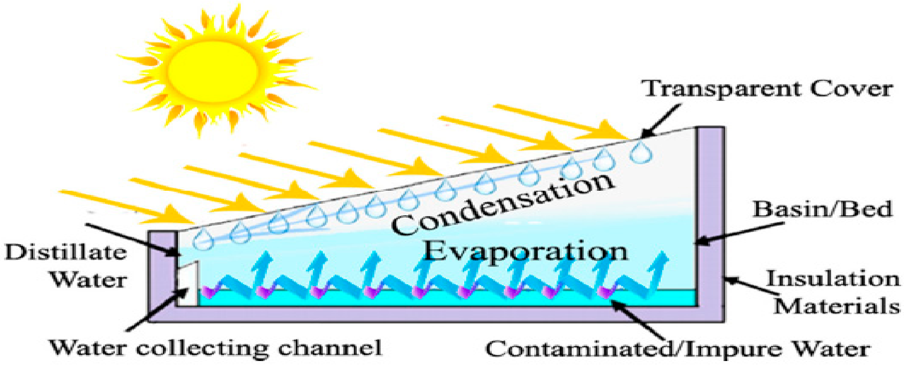


Figure 1. The sketch of a single slope passive solar still [65].

The numerical hourly condensed water production rate per unit area of a solar still (M_{hn}) is calculated [66] by dividing the rate of evaporative heat transfer from basin water surface (q_{ew}) [67] to the latent heat of water evaporation (L) which is shown as the following:

$$M_{hn} = (q_{ew}/L) \times 3600 \text{ kg/m}^2\text{ h} \tag{1}$$

The rate of evaporative heat transfer from the basin water surface (q_{ew}) depends greatly on the differences in the hourly values of temperatures of basin water (T_w) and inner cover (T_g) of the solar still, which is calculated as the following:

$$q_{ew} = h_{ew}\, A_b\, (T_w - T_g) \tag{2}$$

(A_b) is the area of the solar still basin, and (h_{ew}) is the evaporative heat transfer coefficient from the water surface to the condensing cover of the solar still, whose value is based on the values of the saturated vapor pressure at basin water and condensing cover temperatures (P_w and P_g) and convective heat transfer coefficient (h_{cw}). The values of h_{ew} and h_{cw} are calculated by [66]:

$$h_{ew} = 16.273 \times 10^{-3} h_{cw}\ (P_w - P_g)/(T_w - T_g) \tag{3}$$

and

$$h_{cw} = 0.884\ [T_w - T_g + (P_w - P_g) \times (T_w + 273)/268.9 \times 10^3 - P_w]^{1/3} \tag{4}$$

The values of P_w and P_{ic} are obtained according to [68] as follows:

$$P_w = 7235 - 431.45\ T_w + 10.76\ T^2{}_w \tag{5}$$

$$P_g = 7235 - 431.45\ T_g + 10.76\ T^2{}_g \tag{6}$$

Different designs of solar distillation stills were constructed and used to treat water from lakes [48–51,53,69], groundwater [59,70–72], and seawater [52,73–75] in which these are the natural water resources located nearby the remote, rural, and coastal areas. The investigated parameters of treated water in these studies were reported to be acceptable according to the WHO drinking water standards. In a study in Malaysia [51], the treatment of water samples from a lake source was performed using two passive solar stills, which were designed and fabricated using glass (GSS) and polythene film (PSS) as cover materials. It was revealed in the study that the quality parameters of pH, TDS, salinity, nitrate, nitrite, iron, turbidity, and EC after the experiment were in agreement with the acceptable ranges of WHO standards for drinking water [76] (Table 3). Furthermore, GSS was found to be capable of producing improved quality water compared to PSS as the hourly and average daily basin water temperature of GSS were higher than those of the PSS. In another study [69], samples of lake water were treated using two passive and active solar stills whereby the examined parameters of pH, nitrate, iron, sulfate, and turbidity of both solar stills were also in agreement with the WHO standards of drinking water [76]. It was found by Al-Qadami et al. [69] that the active solar still with basin water temperature higher than that of the passive solar still model could produce fresh water with improved quality.

Table 3. The performances of several solar stills after the treatments of lake water [51,69], groundwater [59] and seawater [52] samples, as recommended for the remote, rural and coastal community consumption.

Water Quality Parameters	**PSS [51]**	**GSS [51]**	**Passive Solar Still [69]**	**Active Solar Still [69]**	**SSSB [59]**	**TrSS [52]**	**WHO Standards for Drinking Water [76]**
pH	6.51	6.53	6.62	6.59	7.14	7.7	6.5–8.0
Total dissolved solids (TDS) mg/L	95	28	----	----	45	7.52	600
Total Arsenic (mg/L)	----	----	----	----	≤0.01	----	0.01
Salinity (mg/L)	0.1	0	----	----	Na	0.006	<0.25
Nitrate (mg/L)	0.6	0.4	0.45	0.38	0.74	----	<50
Nitrite (mg/L)	0.03	0.01	----	----	Na	----	<0.05
Fluoride (mg/L)	----	----	----	----	0.02	----	1.5
Chloride (mg/L)	----	----	----	----	10.99	----	250
Hardness (mg/L)	----	----	----	----	33.81	----	200
Iron (mg/L)	0.03	0.02	0.1	0.07	0.00	----	0.3
Sulfate (mg/L)	----	----	0.2	0	0.72	----	250
Turbidity (NTU)	1.37	0.92	1.6	1.43	Na	----	<5
Electrical Conductivity (EC) (µS/cm)	52.5	15.66	----	----	Na	11.6	<250

In another study, groundwater with high arsenic content obtained from a rural community area in India was treated using a single slope single basin (SSSB) solar still [48]. It was observed in the study that the parameters of pH, TDS, total Arsenic, nitrate, fluoride, chloride, hardness, iron, sulfate, and total coliform after conducting the experiment using SSSB [59] conformed with the WHO's ranges of drinking water guideline [76], as given in Table 3. In another study in Malaysia [51], seawater samples were treated using a low-cost passive triangular solar still (TrSS), whereby the results showed that the quality parameters of pH, salinity, TDS, and EC were also in compliance with the WHO standards of drinking water [76] (Table 3).

However, until the present, the investigation on the use of solar still covered with a low-cost polythene film layer and with a black painted stainless steel basin as a treatment technique of the polluted urban grey water has not been reported.

As Malaysia enjoys varied annual average rates of daily solar radiation intensity with ranges between the maximum rates from 700 to 800 W/m^2 and the minimum rates from 500 to 600 W/m^2 [49–52,57,77,78], thus, the daily intensities of solar radiation in Malaysia have a potential to be used in a year for desalination systems using only solar energy such as passive and active solar desalination stills.

In this work, a typical slum nearby an urban household area in Malaysia was selected as a source of contaminated grey water which is located on the opposite side of a building site (100°29′ E and 5°7′ N) located in an urban area in a city in the Perak state, namely Parit Buntar, where the total urban grey water was being accumulated. Poor sanitation of that slum was seen to pose various health risks to the public, and hence, the importance of treating its grey water was perceived. Thus, this study was conducted to evaluate the performance of a low-cost double slope passive solar still by treating the grey water from the aforementioned slum, as well as to analyze the quality, quantity, and cost per liter of the produced water. The cover and basin of the solar still were made from transparent polythene film and black-painted stainless steel trough, respectively, while the frame was made from polyvinyl chloride (PVC). The productivity of the solar stills in other studies [52,60,79] was found to be increased by feeding the lower depth of water in their basins. Accordingly, the collected grey water in this study was fed into the solar still basin at 1 cm depth, and the solar still was named PSSG1, abbreviated. Therefore, the aim of this study was to examine the treatment of grey water originating from one of the typical urban areas in Malaysia by using a low-cost polythene film cover double slope solar still, namely PSSG1, with has 1 cm water depth in its black-painted stainless steel trough in order to evaluate the amount of freshwater production. The study also aimed to analyze the cost per liter and quality of the water produced by PSSG1 whilst comparing its water quality parameters, particularly the values of BOD_5, TSS, TN, TP, turbidity, pH, fecal coliforms, and total coliforms after treatment, with the standards of non-potable grey water reuse guideline [15] and the WHO drinking water standards [80]. The percentages of pollutants removal by PSSG1 were also compared with those of the water produced by different types of grey water treatment techniques in other studies, such as the physical, chemical, and biological treatment processes.

2. Materials and Methods

2.1. Study Area

This work was carried out to examine the treatment of urban grey water collected from a typical urban slum in Parit Buntar urban zone, Perak, Malaysia (Figure 2). The samples of grey water were collected from an urban grey water collection slum (Figures 3 and 4) located approximately in front of a building site (Bank Islam, at the coordinate of 100°29′ E and 5°7′ N), where the total grey water of the urban area was being drained and accumulated. Generally, the Parit Buntar grey water slum contains grey water as discharged from household kitchen basins, shops, laundries, and restaurant kitchen basins which was then becoming diluted with the stormwater runoff. Poor sanitation of that slum seemed to pose various health risks to the public, and hence, the importance of treating its grey water was perceived.

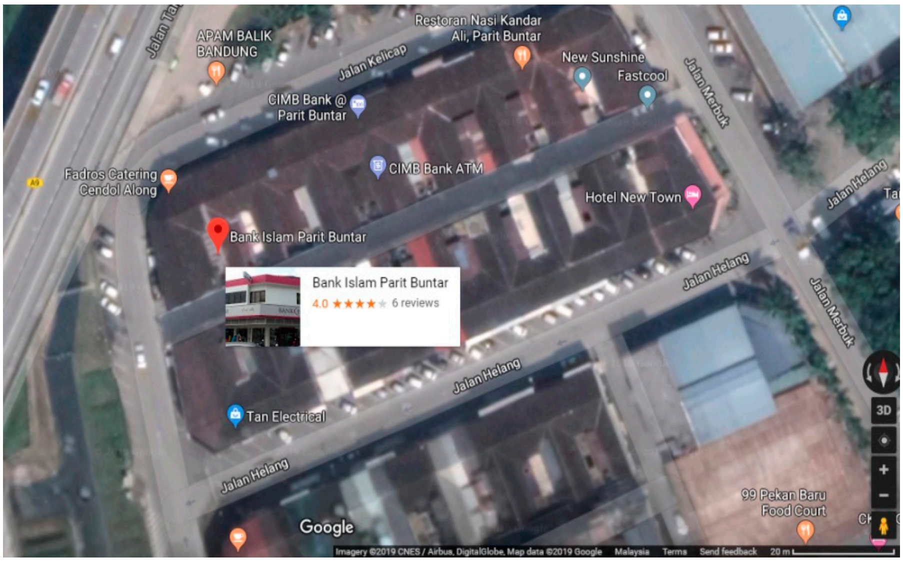


Figure 2. The Google map image of Bank Islam located in Parit Buntar Urban zone, Malaysia.

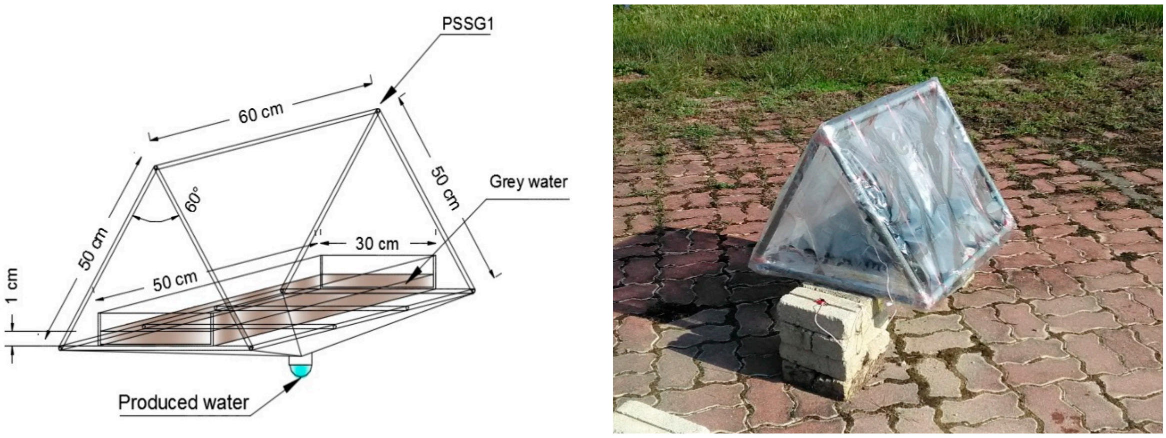
(**a**) (**b**)

Figure 3. The Google map images of Parit Buntar urban grey water collection channels (**a**) and the slum (**b**) in front of Bank Islam.

Figure 4. Photograph of researchers collecting the grey water samples from the slum located in Parit Buntar urban area in front of Bank Islam.

2.2. Experimental Set-Up

In this study, a double slope passive solar still with a transparent polythene film layer as cover, PVC pipes as frame, and black-painted stainless steel trough as basin materials (Figure 5) was designed and fabricated at the research site in the engineering campus of Universiti Sains Malaysia (USM), Malaysia in order to treat the urban households' grey waters. The samples of urban grey water collected from a typical grey water slum in Parit Buntar urban area (Figures 3 and 4), which was nearby USM, were fed into the basin at 1 cm depth (Figure 5).



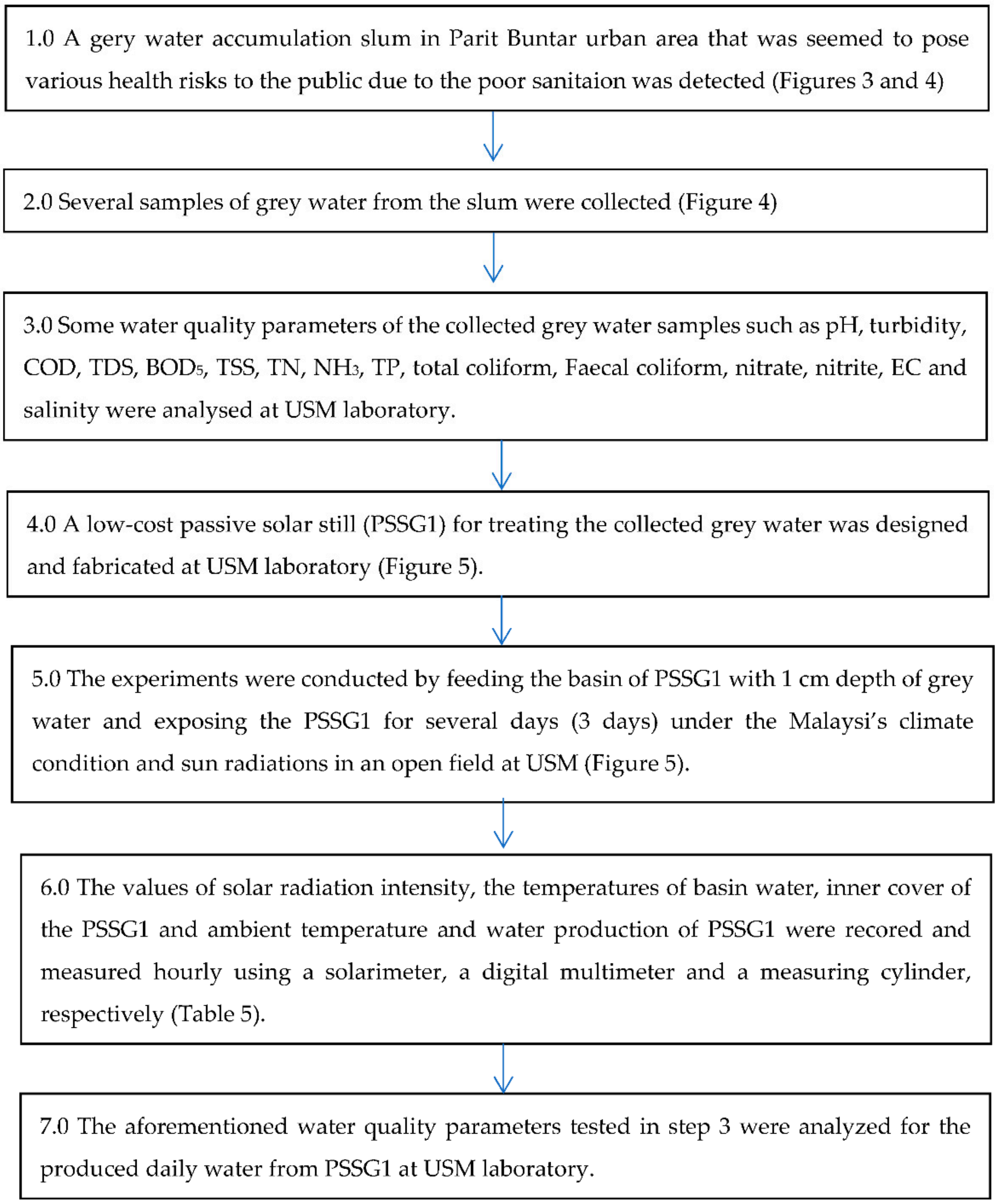
(**a**) (**b**)

Figure 5. The sketch of the solar still, PSSG1 (**a**) and the photograph of the experimental set up of PSSG1 (**b**).

Comparative studies on passive solar stills with different basin water depths of 1.5 cm, 2.5 cm, and 5 cm in Malaysia [52], 2 cm to 12 cm in India [60], and 1 cm, 2 cm, 3 cm, and 4 cm in India [79] were conducted. As the productivity of the solar stills in these studies [52,60,79] was found to be increased by feeding the lower depth of water in their basins, accordingly, the collected grey water in this study was fed into the solar still's basin with 1 cm depth to investigate the performance of the treated grey water in terms of produced water quantity and quality. Hence, the solar still was named PSSG1, abbreviated.

Figure 5 shows the sketch and photograph of the experimental set-up of the tested PSSG1. As can be seen, the solar still frame had a length and width of 60 and 50 cm, respectively. The black-painted basin of PSSG1 had a length of 50 cm, a width of 30 cm, and a depth of 8 cm, with a calculated area of 0.15 m^2 and volume of 0.012 m^3. The solar still was constructed using the cost-effective polythene film cover materials. Compared to the solar still using glass cover (GSS) [51], the use of those materials has made the solar still lighter and more easily portable. In addition, PVC pipes and polythene film have longer duration, i.e., up to 5 years [81], compared to vinyl chloride sheets with durability of two years [82]. Thus, the lifetime of PSSG1 was expected up to 5 years in this work.

Different designs of single and double slope passive solar stills were constructed and tested experimentally in several countries with different climate conditions, such as Saudi Arabia [83], India [56], Egypt [84], Jordan [61], Ivory Cost [68] and Malaysia [52,57] and their performances were studied for durations of 1 day, 1 day, 4 days, 3 days, 1 day, 5 days and 5 days, respectively. Thus, the experiment using PSSG1 was conducted for a period of three days, i.e., on 1, 5, and 10 of April 2019, in order to evaluate the cost per liter/m^2, quantity, as well as the quality of the produced water. Specifically, the quality of the collected grey water and the produced water were analyzed in the environmental lab on the university campus. The above procedures were presented in the following schematic diagram in this section (Figure 6). The total fabrication cost of PSSG1 was around RM 84.14 or USD 20.12 (Table 4). In the experiment, a multimeter was used in order to measure the temperatures of the basin water, solar still inner cover, and the ambient hourly. The solar radiation intensity on the campus was measured every 15 min using a solarimeter. Table 5 shows the details of the models, accuracies, range, percentage errors, and standard uncertainties of the instruments used in the experiment to measure solar radiation intensity, water production, and temperature. The standard uncertainty was determined by Rahbar and Isfahani [85] as $u = (a/\sqrt{3})$, where a is the accuracy of the instrument, and u is the standard uncertainty. In the process, vapors were condensed at the inner side of the PSSG1 transparent cover. The condensed water was moved down and collected at the bottommost of the polythene film cover of the solar still (Figure 5). A measuring cylinder was used to measure the amount of the collected condensed water. Figure 7 illustrates the collected grey water from a typical slum in the study area (a) and the water produced by PSSG1 (b).



1.0 A gery water accumulation slum in Parit Buntar urban area that was seemed to pose various health risks to the public due to the poor sanitaion was detected (Figures 3 and 4)

2.0 Several samples of grey water from the slum were collected (Figure 4)

3.0 Some water quality parameters of the collected grey water samples such as pH, turbidity, COD, TDS, BOD_5, TSS, TN, NH_3, TP, total coliform, Faecal coliform, nitrate, nitrite, EC and salinity were analysed at USM laboratory.

4.0 A low-cost passive solar still (PSSG1) for treating the collected grey water was designed and fabricated at USM laboratory (Figure 5).

5.0 The experiments were conducted by feeding the basin of PSSG1 with 1 cm depth of grey water and exposing the PSSG1 for several days (3 days) under the Malaysi's climate condition and sun radiations in an open field at USM (Figure 5).

6.0 The values of solar radiation intensity, the temperatures of basin water, inner cover of the PSSG1 and ambient temperature and water production of PSSG1 were recored and measured hourly using a solarimeter, a digital multimeter and a measuring cylinder, respectively (Table 5).

7.0 The aforementioned water quality parameters tested in step 3 were analyzed for the produced daily water from PSSG1 at USM laboratory.

Figure 6. A schematic diagram (flowchart) presenting the methodology procedures conducted at USM.

Table 4. Fabrication costs of PSSG1.

Items	Quantity	Unit Cost (RM)	Cost (RM)
Polythene film cover (0.15 mm thickness)	1.2 m^2	RM 1.90/m^2	2.28
PVC pipe frame (15 mm diameter)	4.8 m	RM 6.20/m	29.76
Stainless steel tray	1	40.00	40.00
Plastic rope	30 m	RM 12.00/roll	3.60
Transparent tape	1	2.50	2.50
Flat black spray	1	6.00	6.00
Total cost			84.14
Note: USD 1 ≈ RM 4.18			

Table 5. The model, accuracy, range, percentage errors and standard uncertainty of the experimental instruments.

Instruments	Model	Accuracy	Range	% Error	Standard Uncertainty
Digital multimeter	EM382	±1 °C	0 to 100 °C	1	±0.5 °C
Solarimeter	SM206	±1 W/m^2	0 to 3000 W/m^2	0.5	±0.5 W/m^2
Measuring Cylinder		±0.5 mL	0 to 50 mL	0.5	±0.3 mL

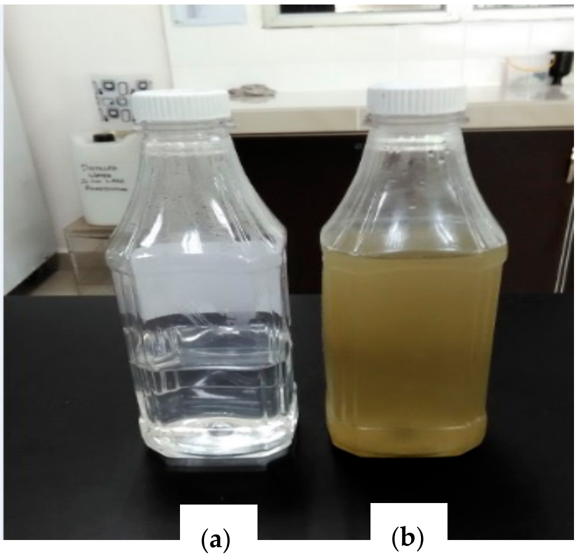


Figure 7. Photograph of the water produced by PSSG1 (**a**) and the grey water collected from the Parit Buntar urban area (**b**).

3. Results and Discussion

3.1. Effects of Solar Radiation Intensity on Temperatures of Water, Inner Cover of PSSG1, and Hourly Water Production

Table 6 shows the variations of average solar radiation intensity (I_s), the average temperatures of water (T_w), PSSG1's inner cover (T_{ic}), and ambient air (T_a), as well as the cumulative productivities (M_c) of the solar still from 8 a.m. to 6 p.m. within the three experimental days on the 1, 5 and 10 April 2019. As can be seen, with the rise in the average solar intensities, all the average temperatures (ambient, basin water, and PSSG1's inner cover) have increased, which resulted in an increased amount of water production (Table 6). In detail, the highest average solar radiation intensity took place on 10 April 2019 with the rate of 735.00 W/m^2, in which this condition caused the average temperatures (T_w and T_{ic}), and M_c to achieve the values of 48.45 °C, 41.23 °C, and 4.11 L/m^2, respectively.

Table 6. The average values of T_W and T_{ic} of PSSG1, I_s and T_a and the cumulative productivity of PSSG1 (M_c) obtained from 8 a.m. to 6 p.m. for the three experimental days.

Date	**Average I_s (W/m^2)**	**Average T_a (°C)**	**Average T_W (°C)**	**Average T_{ic} (°C)**	**M_c (L/m^2·d)**
01.04.2019	516.47	31.04	44.73	38.02	2.81
05.04.2019	652.23	32.09	47.65	40.38	3.74
10.04.2019	735.00	32.36	48.45	41.23	4.11

The plot of Is values obtained from 8 a.m. to 6 p.m. on the third experimental day (10 April 2019) is shown in Figure 8. Meanwhile, the plot of hourly values of T_w and Tic versus the values of M_h of PSSG1 on this day is shown in Figure 9. The average values of I_s, T_w, and T_{ic} of PSSG1 and T_a were found to be 735 W/m^2, 48.45 and 41.23 °C, and 32.36 °C, respectively, on this day (Table 6). The highest values of T_w, T_{ic} of PSSG1, and T_a were recorded at 57, 47, and 36 °C respectively at 2:00 p.m. once the I_s reached the highest value of 1277 W/m^2 (Figures 8 and 9). The rise and fall of these temperatures corresponded to the growth and decline in the solar radiation intensity all over the day (Figures 8 and 9). Thus, these results conform to the results obtained in other studies [48,51,52]. As seen in Figures 8 and 9, the water production by PSSG1 corresponds to the solar radiation intensity and water temperature. The highest evaporation from the PSSG1's basin water was observed during the experiment at the highest PSSG1 water temperature at 2:00 p.m., which corresponds to the increase in the solar radiation intensity to the highest value of 1277 W/m^2 at that time (Figures 8 and 9).

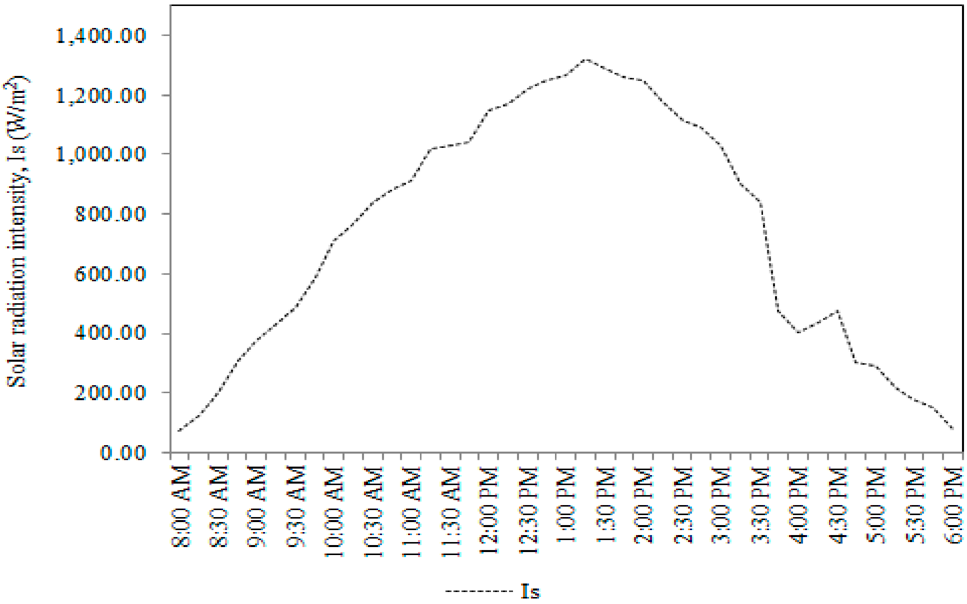


Figure 8. Variations of solar radiation intensity (I_s) from 8 a.m. to 6 p.m. on the third experimental day (10 April 2019).

The highest hourly water production by the solar still, i.e., 0.70 L/m^2, was recorded at 3:00 p.m. even though the solar radiation intensity and the water temperature had reduced from 2:00 to 3:00 p.m. (Figures 8 and 9). This result shows that there was a one-hour time lag between the peak values of solar radiation intensity and water temperature. Such a condition was similarly reported in other previous studies [48,49,51,52,86–93].

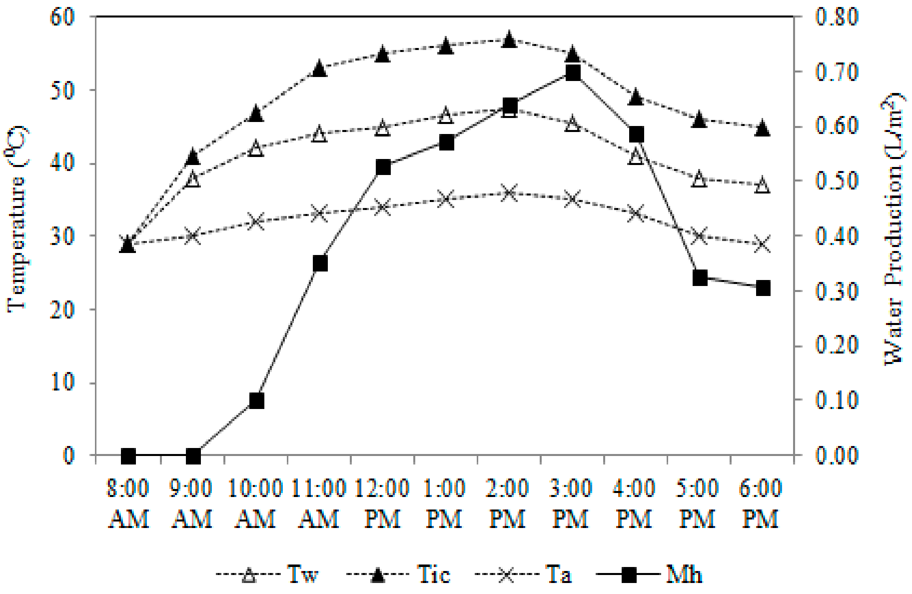


Figure 9. Variations of temperatures of water and inner cover of PSSG1, ambient temperature and PSSG1's hourly water production from 8 a.m. to 6 p.m. on 10 April 2019.

3.2. Cumulative Water Production of PSSG1

The maximum values of the cumulative productivity of PSSG1 (M_c) on the third experimental day (10 April 2019) were shown in Figure 10. The solar still produced the maximum amount of 4.11 L/m^2 of potable water during the experimental day. The maximum cumulative productivity of this low cost solar still was higher than those of solar stills examined by previous studies in Malaysia [47,48,51,52,57], India [56,60,70,94], Egypt [84,95], Jordan [61,96], Nigeria [97] and Pakistan [98], whereby the maximum cumulative productivity values were recorded by these studies at 2.10, 2.227, 3.22, 1.55, 2.26, 2.54, 2.10, 1.91, 3.03, 4.10, 3.58, 2.99, 3.85, 2.396, and 3.25 L/m^2·d, respectively.

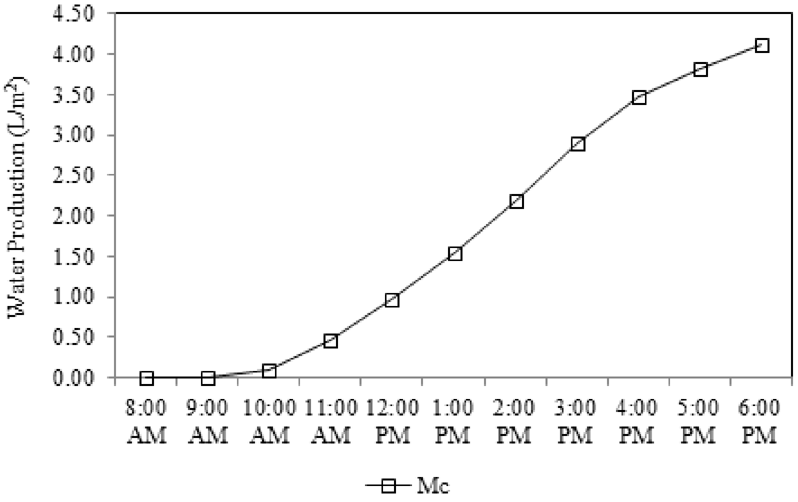


Figure 10. The values of cumulative water production of PSSG1 (M_c) from 8 a.m. to 6 p.m. on 10 April 2019.

3.3. Cost Study and Analysis of the Produced Water by PSSG1

As shown in Table 4, the assumed fixed cost (F) [95] of PSSG1 is USD 20.12, which is equal to its fabrication cost. Assuming that n is the estimated lifetime of PSSG1, F is the fixed cost, V is the variable cost, and C is the total or cumulative cost, the average rate of the cost of the distillate yield was then calculated. Based on Equation (7), the total cost of the solar still is given as [95]:

$$C = F + V \tag{7}$$

As V equals n × 0.3 × F, then $C = F + 0.3 \times F \times n$; therefore, the total cost of PSSG1 with the expected still lifetime of five years is calculated as:

$$C = 20.12 + 0.3 \times 20.12 \times 5 = \text{USD } 50.30$$

The average daily productivity of PSSG1 was estimated from the experimental day as 4.11 $L/m^2 \cdot day$, assuming that solar still would operate 300 days in the year [95]. The obtained total water production of PSSG1 during the solar still life was $M_{PSSG1} = 6165\ L/m^2$. Therefore, the cost per liter/m^2 from the PSSG1 was calculated as: 50.30/6165 = USD 0.0082. Furthermore, it was also observed that the cost per liter/m^2 of PSSG1 in this study was much lower (i.e., USD 0.0082) than other solar stills reported by previous studies in Pakistan [98], India [56,79,99–103], Malaysia [50,82], Egypt [95,97,104–107], Canada [52], Saudi Arabia [108], Iran [109–113] which reportedly costed at the rates of USD 0.063, 0.2, 0.024, 0.0264, 0.026, 0.86, 0.026, 0.054, 0.105, 0.015, 0.065, 0.049, 0.08, 0.048, 0.06, 0.14, 0.18, 0.039, 0.13, 0.023, 0.019, 0.105 and 0.1652, respectively.

3.4. Quality Analysis of the Grey Water Influent and Effluent

Based on the laboratory analysis results of the quality of the collected grey water (Table 7) and the grey water quality data (Table 1), it can be implied that the grey water sampled from a typical slum nearby the Parit Buntar urban area can be categorized as low-strength grey water. By using PSSG1 in treating the collected grey water, the parameters concentrations of pH, turbidity, COD, TDS, BOD_5, TSS, TN, NH_3, TP, total coliform, fecal coliform, nitrate, nitrite, EC and salinity decreased in the effluent produced as follows: In Day 1, the values decreased from 7.42, 79.1 NTU, 84 mg/L, 240 mg/L, 18.06 mg/L, 176 mg/L, 6.649 mg/L, 6.0 mg/L, 4.3 mg/L, 1020/mL, 110/mL, 7.0 mg/L, 0.298 mg/L, 160.2 μS/cm and 0.07 mg/L to 7.1, 2.6 NTU, 9.2 mg/L, 87.03 mg/L, 0.5 mg/L, 3.1 mg/L, 0.223 mg/L, 0.07 mg/L, 0.01 mg/L, 10/100 mL, 3/100 mL, 1.1 mg/L, 0.04 mg/L, 48.3 μS/cm and 0.06 mg/L. In Day 2, the values decreased to 6.9, 2.3 NTU, 8.7 mg/L, 69.31 mg/L, 0.3 mg/L, 2.6 mg/L, 0.142 mg/L, 0.04 mg/L, 0 mg/L, 8/100 mL, 3/100 mL, 0.95 mg/L, 0.03 mg/L, 43.6 μS/cm and 0.03 mg/L; and in Day 3, the values decreased to 6.7, 2 NTU, 8 mg/L, 61.49 mg/L, 0.2 mg/L, 2 mg/L, 0.129 mg/L, 0.03 mg/L, 0 mg/L, 7/100 mL, 2/100 mL, 0.9 mg/L, 0.03 mg/L, 41.2 μS/cm and 0.02 mg/L (Table 7). Thus, these results indicate that the quality of the produced water by PSSG1 was improved on Day 3 compared to the quality parameters on Day 1 and Day 2. This was because the average solar radiation intensity was obtained the highest at 735 W/m^2 and the average still basin water temperature reached the highest value of 48.45 °C on Day 3 (Table 6).

In a comparative study by Riahi et al. 2018 [51], the solar still, GSS, obtained a higher average of Tw which resulted in producing an improved quality of freshwater compared to the water produced by PSS [51]. In another study by Al-Qadami et al. [69], the active solar still, which was integrated with an external heat source of a solar power system, had a higher average basin water temperature than the passive solar still water temperature throughout the experiment; this shows that use of active solar still resulted in producing better quality freshwater compared to the passive solar still which does not use the external energy (Table 3). As seen in Tables 6 and 7, PSSG1, which had a higher average basin water temperature on Day 3 (48.45 °C), produced a better quality of freshwater compared to those produced on Day 1 (44.73 °C) and Day 2 (47.65 °C). Therefore, the above results conform to the results from other comparative studies [51,69]. The parameters of the produced water by this low-cost solar still were also in compliance with the standards of the non-potable grey water reuse guideline offered by Li et al. [15], WHO-2017 drinking water standards (Table 7 [80]), and the Malaysian class I drinking water standards (Table 7 [114]).

Table 7. Performance evaluation of the solar still (PSSG1) used for the treatment of the grey water of Parit Buntar urban area.

Water Quality Parameters	Grey Water Collected from the Urban Area	Generated Water by PSSG1 on Day 1	Generated Water by PSSG1 on Day 2	Generated Water by PSSG1 on Day 3	WHO-2017 Drinking Water Standards (WHO, 2017) [80]	Malaysia Class I Drinking Water Standards (EQR, 2006) [114]
pH	7.42	7.1	6.9	6.7	6.5–8.0	6.5–8.0
Chemical Oxygen Demand (COD) (mg/L)	84	9.2	8.7	8.0	<10	<10
Biochemical oxygen demand (BOD_5) (mg/L)	18.06	0.5	0.3	0.2	<2	<1
Salinity (mg/L)	0.07	0.06	0.03	0.02	<0.25	<0.50
Total dissolved solids (TDS) (mg/L)	240	87.03	69.31	61.49	<600	<500
Total suspended solids (TSS) (mg/L)	176	3.1	2.6	2	<250	<25
Ammonia, NH_3 (mg/L)	6.0	0.07	0.04	0.03	<1.5	<1.5
Turbidity (NTU) (mg/L)	79.1	2.6	2.3	2.0	<5	<5
Nitrate (mg/L)	7.0	1.1	0.95	0.9	<50	<50
Nitrite (mg/L)	0.298	0.04	0.03	0.03	<0.05	<0.05
Total nitrogen (TN) (mg/L)	6.649	0.223	0.142	0.129	<1	<1
Total Phosphorus (TP) (mg/L)	4.3	0.01	0.0	0.0	<0.05	<0.05
Faecal Coliform (CFU/100 mL)	110	3	3	2	<10/100 mL	<10/100 mL
Total Coliform (CFU/100 mL)	1020	10	8	7	<100/100 mL	<100/100 mL
Electrical conductivity (µS/cm)	160.2	48.3	43.6	41.2	<250	<1000

In addition, PSSG1 was observed to be capable in removing pollutants from the grey water on the third experimental day, such as COD, BOD_5, turbidity, TDS, TN, TSS, TP, NH_3, total coliforms, faecal coliforms, nitrate, nitrite, EC and salinity, at the highest rates (i.e., by 90.47%, 98.89%, 97.47%, 74.37%, 98.05%, 98.86%, 100%, 99.50%, 99.31%, 98.18%, 87.14%, 89.93%, 74.28% and 71.42%, respectively). These rates were found to be higher than the pollutants removal rates through other techniques, such as the physical process by March et al. [16] and Itayama et al. [17], the chemical treatment by Lin et al. [25] and Pidou et al. [26], and the RBC treatment by Friedler et al. [28], as shown in Table 2, respectively. Therefore, it was concluded that the grey water treatment using PSSG1 in this study was considerably more efficient compared to other treatment processes, such as physical [16–23], chemical [25,26], and biological [7,11,28–30,32–36] treatment systems. This was due to PSSG1 being noted to be capable of producing fresh directly without requiring any pre- and post-treatment processes.

Overall, the grey water treatment using PSSG1 in this study has fulfilled the four required principles of grey water treatment for reuse applications as mentioned by Nolde, 2000 [11], which are aesthetics, sanitary safety, environmental acceptance, and financial feasibility. Most of the grey water treatment methods (such as physical, chemical, and biological treatments) employ the solid–liquid separation stage in the pre-treatment system, including the septic tank, and screen and filter bags, in order to decrease the number of particles [15]. This work, on the other hand, has identified that the use of separation steps in the treatment processes might not be needed with the use of PSSG1.

4. Conclusions

In summary, the energy from the sun, which is a sustainable energy source, can be well absorbed by a low-cost solar still and then transformed as heat for treating a typical low-strength urban grey water. This work investigated the use of a low-cost passive solar still, namely, PSSG1, in treating the grey water collected from a typical urban grey water slum to experiment with the treatment process under the Malaysian outdoor tropical climate conditions. It was found that PSSG1 was capable of removing the pollutants of COD, BOD_5, turbidity, TDS, TSS, TN, TP, NH_3, total coliform, fecal coliform, nitrate, nitrite, EC, and salinity by 90.47%, 98.89%, 97.47%, 74.37%, 98.86%, 98.05%, 100%, 99.50%, 99.31%, 98.18%, 87.14%, 89.93%, 74.28%, and 71.42%, respectively, from the contaminated grey water which accredited that the parameters of the water produced by this solar still were in compliance with the standards of the restricted and unrestricted non-potable grey water reuse guideline, the World Health Organization (WHO) and the Malaysian class I drinking water. It was also determined that obtaining the highest average of the bain water temperature in PSSG1 resulted in producing the highest daily amount of water at 4.11 L/m^2 and the improved quality of freshwater. Furthermore, the cost per L/m^2 of PSSG1 was significantly low, i.e., USD 0.0082, which affirmed that this solar still can be a potentially beneficial and economical approach to treating grey water in urban areas. Therefore, PSSG1 can be used as a practical alternative for treating low-strength grey water collected from various urban household areas in Malaysia in order to assist pollutants removal from the drained urban grey waters.

Directions for the Further Research

The distillate water produced by the solar distiller is deficient in minerals and fluoride concentration, and hence, some minerals and fluoride salts may be added to the distillate [59] to be in accordance with the requirements per drinking water quality standards, which state 1.5 mg/L in WHO, 2008 [76]. Meanwhile, Based on the studies reported by Parsa et al., 2021 [65], some thermally resistant waterborne pathogens such as *E. coli* and *Enterococcus faecalis* are able to survive in distiller basin water with temperatures up to 55 and 65 °C, respectively; thus, the optimal temperature of water in the distiller should reach above 65 °C to disinfect the distiller basin water and destroy those pathogens; therefore, one of the best solutions is by integrating the passive solar still in this work with the external energy sources such as the photovoltaic thermal modules recommended by [115–117] to heat the basin water and increase the water temperature above 65 °C to avoid transmitting the pollutants and pathogen into the distillate. The amount of water production of the solar still and the quality of the produced water will also be improved. However, the cost of the modules should be considered. The performances of the passive solar still in this work and the future planned solar still integrated with the photovoltaic thermal modules may also be investigated for treating the agro-based industrial wastewater (AIW) such as the wastewaters discharged from an olive oil mill, sugar industry, pulp and paper mill, palm oil mill, coffee industry and vegetable oil refinery in the future in Malaysia and comparing their performances with the presentations of the electro-coagulation processes stated by Rakhmania et al. [118].

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