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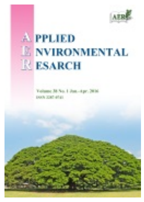

Organic Matter, Solid and Pathogen Removals from Black Water in a Pilot-Scale Solar Septic Tank

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Abstract

Demonstrating the operational feasibility of a solar-powered septic tank as an alternative and sustainable sanitation option for communities was presented in this study. The efficiency and technical feasibility of a solar septic tank (SST) were tested and evaluated in pilot scale for treatment of black water from communal toilets. The system consisted of a modified septic tank equipped with a disinfection chamber inside the tank. Solar radiation was collected as a heat source for heating and disinfection. The system could achieve high removal efficiencies of total chemical oxygen demand (TCOD), 5-day biological oxygen demand (BOD_5), total solid (TS), and total volatile solid (TVS) of 97%, 94%, 91% and 96%, respectively. The inactivation efficiencies of *E. coli* and total coliforms in the SST were about 2.2 log reduction. The increased temperature inside the septic tank could help to inactivate pathogens and reduce the environmental issues related to conventional fecal sludge management. In turn, this improved the water quality of groundwater and surface water and minimize health risks. Influence of operational conditions including organic/nutrient loading rate and ratio between TCOD and TKN in the black water on the performance of the SST were discussed.

Keywords: Black water; Community scale; Solar septic tank; Treatment performance

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Introduction

The United Nations Sustainable Development Goals (UNSDG) target clean water and sanitation (Goal 6) for all, yet it is estimated that more than 2.4 billion people still live without access to basic sanitation, especially in most developing countries [1]. According to the United Nations [1] and World Health Organization [2] reports, lack of the adequate sanitation facilities has caused negative impacts not only environmental pollutions, but also serious water borne diseases infection to human. Due to large investment as well as high operation and maintenance costs, most of the developing countries could not construct centralized sewage treatment plants. Therefore, there is a need to develop an appropriate onsite sanitation system to receive and treat the black water or/and grey water. Alternatively, some cost-effective and implementable solutions by using on-site wastewater treatment technologies such as cesspools and septic tanks, as primary treatment devices to treat sewage or black water, are more practically feasible [3], but their effluents still contain relatively high concentrations of BOD_5 and *E. coli* [4]. Septic tank is mostly used for black water treatment in Thailand, as well as in the majority of households in South-East Asian countries. Recent surveys of Koottatep et al. [5–6] and the Government of Thailand [7] found the efficiency of these on-site treatment systems to still contain high concentrations of organic matters and fecal microorganisms, causing several pollutions of the nearby storm sewers and water courses. The report of illness [2] showed that the major water borne diseases infection were diarrhea, poisoning food, and unspecified dysentery diseases. Numbers of diarrhea case are approximately 1 million per year.

Septic tank is usually watertight and has two main processes taking place: settling of particles and decomposition of accumulated solids by anaerobic digestion. The septic tank is classified as a primary treatment (or sedimentation basis) with respect to remove organic matters or solids from the raw wastewater. Typical performance for the removal of those pollutants is mainly due to the separation solid particles with a density higher than surrounding water by gravitational settling [8]. The treatment efficiency of septic tanks depends mainly on retention time and temperature. The design of a septic tank has to ensure the removal of settleable solids as much as possible biodegradation processes of soluble organics. Normally, retention time in septic tank are designed in the range of 1–3 d. The treatment efficiency of a conventional septic tank is quite low with BOD_5 reduction of around 25–50% [9–10]. Due to large area requirement, increasing the retention time is not usually practicable. Thus, increasing temperature in the septic tank should be a reasonable measure to increase the anaerobic digestion rate and pathogen inactivation. Koottatep et al. [11] developed solar septic tanks and reported that the removal efficiencies of septic tanks operating at temperatures of 40, 50, 60 and 70˚C were more than 80% for TCOD and BOD_5 and *E. coli* reductions were 4–6 logs. Pussayanavin et al. [12] reported that a laboratory-scale septic tank operating at 40˚C had higher TCOD and TS removal efficiencies than a conventional septic tank. The optimal hydraulic retention time (HRT) of 24 h resulted in the highest removal of TCOD, BOD_5 and TS from the septic tank effluent.

One of the innovative sanitation technologies is “SST”. Because of the potential of solar energy applications in Thailand [13], it would be attractive that anaerobic digestion efficiency in the septic tank could be improved by heating from solar energy. A modified conventional septic tank with solar-heated water is considered to be an effective on-site sanitation technology. The solar septic tank system improves on the traditional septic tank by harnessing solar energy via water filled, hollow tube solar collectors that use energy from sunlight to heat water. This study was conducted to investigate the treatment efficiency of a pilot-scale SST treating black water from communal toilet. The temperature increases inside the SST unit as well as organic, solid and pathogen removal efficiencies were measured.

Material and methods

A pilot-scale testing of SST was conducted under actual conditions of fluctuating flow rate, ambient temperature and black water characteristics at communal toilets located at the Asian Institute of Technology Campus, Pathumthani Province, central Thailand. (Figure 1). The SST was made of polyethylene polymer with an effective volume of 1,000 L. Temperatures in the SST were increased by circulating hot water generated from vacuum tube solar collector (VTSC) through a heat transfer equipment - spiral copper. The hot water is automatically pumped at a rate of 5 L min^{-1} when temperatures of the hot fluid become more than 40°C. The SST unit was insulated with polyurethane to minimize the heat loss. The VTSC, Figure 1(c), has 63 vacuum tubes with 12 m^2 exposed area and peak watts of 2.8 kWp. The vacuum tubes absorb solar radiation and transfer heat to the fluid. There is no heat source storage to supply heat during the night period.

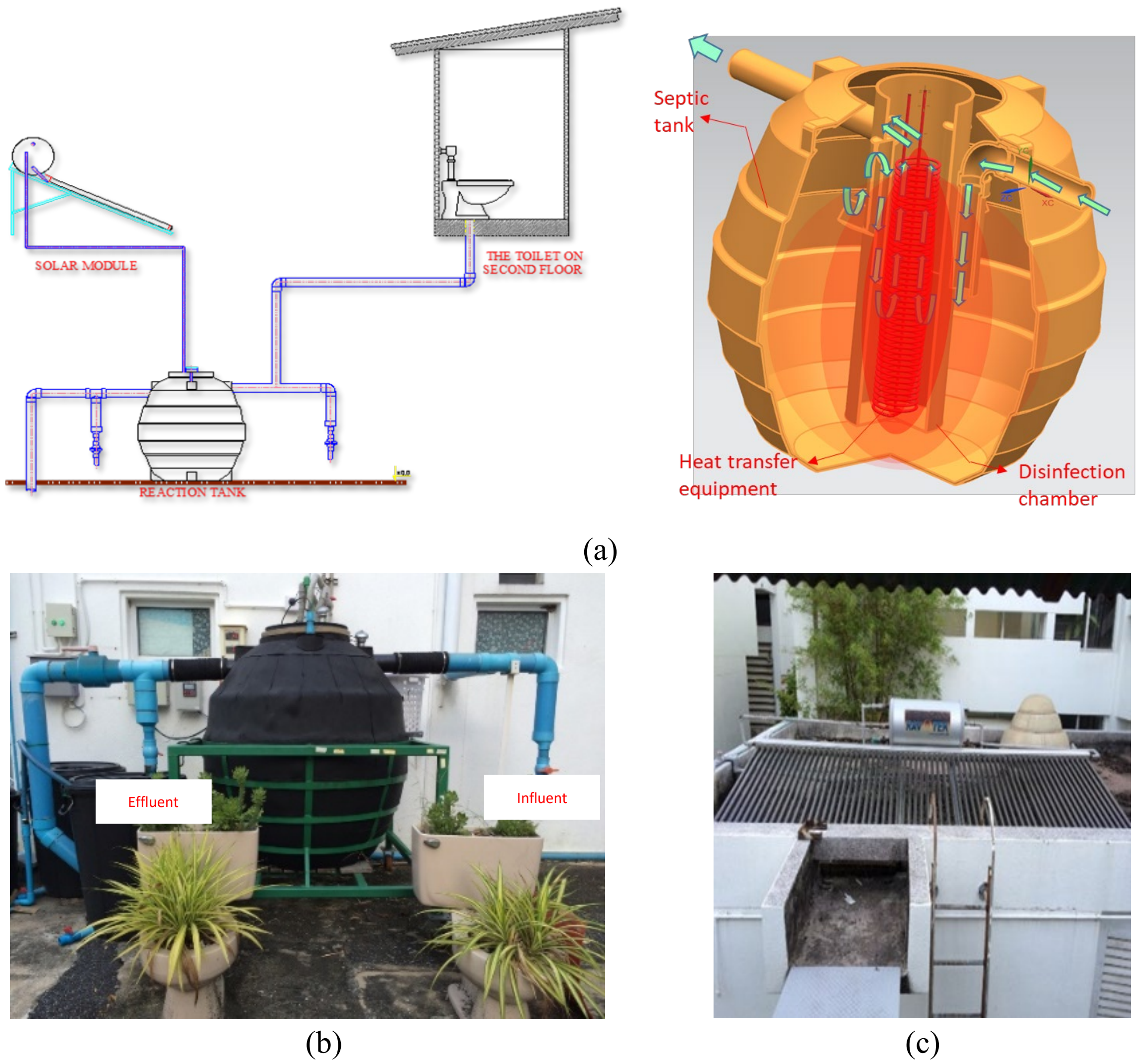

Figure 1 Solar septic tank system - (a) solar septic tank overview (b) SST unit (c) vacuum tube solar collector.

A disinfection chamber (inner-core chamber) with a volume of 60 L was inserted in the middle of the SST unit. Further, and perhaps more vitally, the effluent passes through the smaller inner-core chamber where the temperature is in excess of 55˚C which pasteurizes it, inactivating the fecal pathogens Figure 1(a). Temperatures inside the disinfection chamber and the SST and ambient temperature were monitored by sensors (PT-100 type HDP/7) and a temperature indicator box for PT-100 sensor. The data of solar radiations (15˚ inclined plane) was provided from a meteorological station of Department of Energy Engineering at Asian Institute of Technology. During the 12-month experiments, the SST received the black water containing feces, urine, water and toilet paper from flushing toilets (single occupancy facility) designated for female uses (6–10 L water/flush) with more than 40 users per day. The average flow of black water of about 172±938 L d^{-1} was measured in-situ by a flow counter. The influent, effluent and sludge samples were drawn periodically to enable physical, chemical and biological monitoring of the systems. After flushing the toilet once to clear the outflow pipe of any residual materials, the effluent samples were collected effluent in a 10 L bucket from the outflow pipe during a second flush. pH of the septic tank influent and effluent were found to be similar, being about 7–8, appropriate for growth of anaerobic microorganisms. The influent and effluent samples (composite sampling) were collected once a week for analyses of TCOD, SCOD, BOD_5, TS, TVS, TKN, total coliforms and *E. coli* concentrations according to standard methods [14–15]. The short-term variations of the flow rate or influent volume were caused by an intermittent flow pattern of liquid wastes that vary depending on the institutional activity/holiday (opening times vary). Therefore, these oscillations in the influent where the samples were not designed to collect and analyse. The following is Eq. 1 for removal efficiency (%). The influent and effluent concentrations were calculated.

Results and discussion

The experiments for pilot-SST were conducted for about 12 months and the results obtained are described below.

1) Temperature and power output characteristics

Central Thailand experiences three seasons which are winter (from October to February), summer (from February to May) and rainy (from May to October); there is no significant difference in temperatures among the three main seasons. According to the data collected by Asian Institute of Technology in 2016, depending mainly on time of day, the ambient temperatures fluctuated in the range of 37˚C. The intensity of solar radiation was quite high with the peak at noon time of about 900 W h^{-2}.

Figure 2 reveals the temperature profile inside the SST to be stable at about 38˚C, while the temperatures in the disinfection chamber were higher at around 43˚C. The temperature in the disinfection chamber depended mainly on the intensity of solar energy (Figure 3) in which the maximum temperature of 47˚C occurred during the period of 12.00–15.00 h.

The generated energy from the VTSC and the WHR units was calculated by the following Eq. 2 [16].

The VTSC did not generate energy from 12 am to 8 am but it peaked at noon at around 20 kW. The energy decreased after 4 pm because solar radiation reduced in the evening and there was no energy storage source (Figure 3). The practical application of the SST for treatment of black water at other provinces/countries is proposed by considering the primary factors such as solar radiation (daily and seasonal variability), ambient temperature and solar duration time. The design of structure and size of a solar collector panel should be properly done to achieve the treatment objectives.

Removal efficiency (%) = [(Influent-Effluent)/Influent] x 100 (Eq. 1)

$$P\ (kW) = \frac{V \times \gamma \times C \times \Delta T}{t} \quad \text{(Eq. 2)}$$

Where P = generated energy (kW); V = volume of hot water storage tank, (L); γ = density (kg L^{-1}); C and specific heat of water (kj kg K^{-1}); ΔT = difference in temperature between time i and j; and t = time (sec)

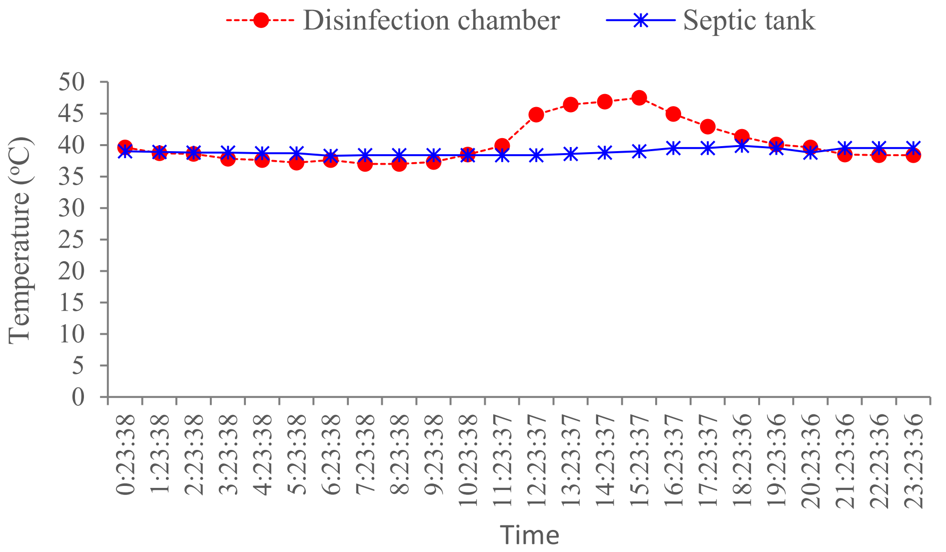

Figure 2 Temperature profile in SST.

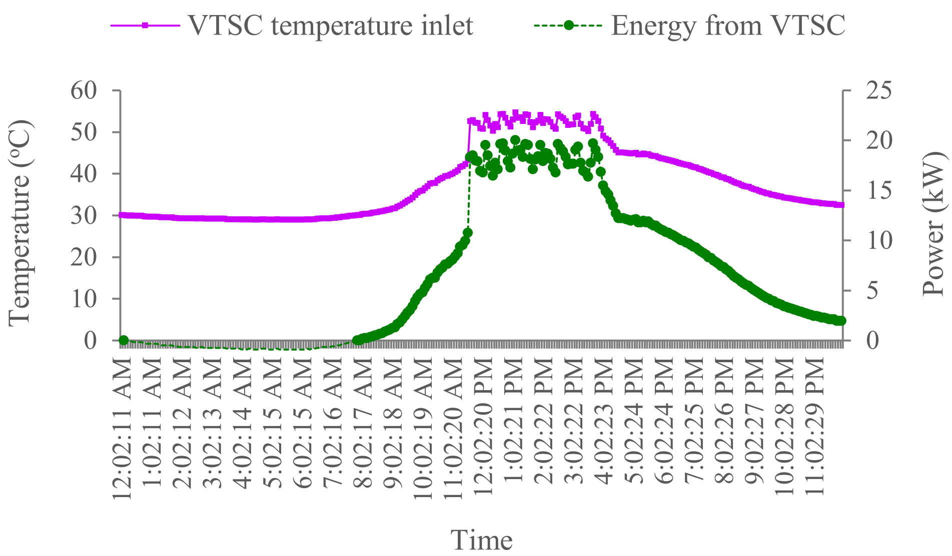

Figure 3 Temperature and energy profile of VTSC + disinfection chamber.

2) Loading rate and TCOD/TKN ratio

The average values of TCOD, BOD_5, TS, TVS and TKN loading rates shown in Figure 4, were about 18.2±8.4 kg m^{-3} d^{-1}, 4.1±2.2 kg m^{-3} d^{-1}, 9.4±4.3 kg m^{-3} d^{-1}, 8.1±4.0 kg m^{-3} d^{-1} and 0.7±0.3 kg m^{-3} d^{-1}, respectively. The TCOD/TKN ratios were found to be from 14.1 to 36.6. During the operation period, due to the change of proportion of the wastes (feces, urine, anal cleansing water and tissue paper) contained in the black water and the user variation per day, the high fluctuations of the values of loading rates and TCOD/TKN ratio were observed. Generally, due to varying of feces quantity and volumes of flushing water, OLRs of the black water were found to fluctuate in the range of 0.5–1.3 kg m^{-3} d^{-1} [5].

3) Organic matters removal

Figure 5 presents the results of organic matter removal in the SST during the 1-year operation. The influent TCOD, SCOD and BOD_5 concentrations varied in the range of 5,000–20,000, 1,000–3,000, 1,000–5,000 mg L^{-1}, respectively, with the average values being about 10,000, 1,500 and 2,000 mg L^{-1}, respectively. The influent concentrations were found to fluctuate caused by fluctuating number of users and the difference in the volume of flush water from the flush toilets. Nevertheless, the effluent TCOD and BOD_5 concentrations could be maintained at approximately 200 and 100 mg L^{-1}, respectively, or achieving the TCOD and BOD_5 removal efficiencies of 97% and 94%, respectively (averaged values from 50 samples). Seabloom et al. [17] reported that the septic tank system operated at ambient temperature was able to remove only 25–50% of BOD_5. Similar to the previous study of Bodik et al. (2000) [18], operating septic tanks at the temperature more than 30°C was able to promote the decomposition (stabilization) of organic matter by biological action. A spatial survey by Koottatep et al. (2014) [6] found that the treatment efficiencies of the conventional septic tank to be low (less than 60 % removal of organic matters) and the septic tank effluent still contained high concentrations of organic matter and pathogens (about more than 200 mg L^{-1} of TBOD and 106 CFU mL^{-1} of *E. coli*). The conventional septic tank effluent has been identified as a major source of surface and ground water pollution in Thailand. Because septic tank effluent still contains high concentrations of the pollutants, post treatments and techniques to improve septic tank performance are required. Draaijer et al. (1992) [19] and Al-Jamal and Mahmoud (2009) [20] researched on a UASB septic tank to treat sewage or black water, found the removal efficiencies of TBOD and TCOD to be better than the conventional septic tank alone. However, due to clogging problems and requirement of high skilled operation, the UASB-septic tank is difficult to be applied at household communities, and required high maintenance cost. Thus, having high treatment efficiencies, and low operation/maintenance cost, the solar septic tank has been proposed as an effective on-site wastewater treatment technology.

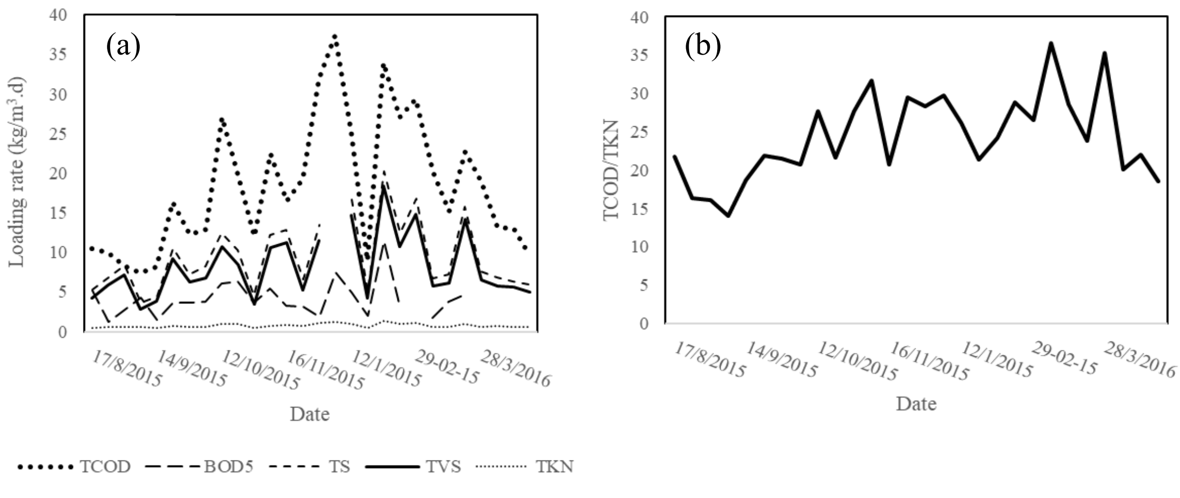

Figure 4 (a) Loading rate of TCOD, BOD_5, TS, TVS and TKN (kg m^{-3} d^{-1}) and (b) Ratio between TCOD and TKN in the black water.

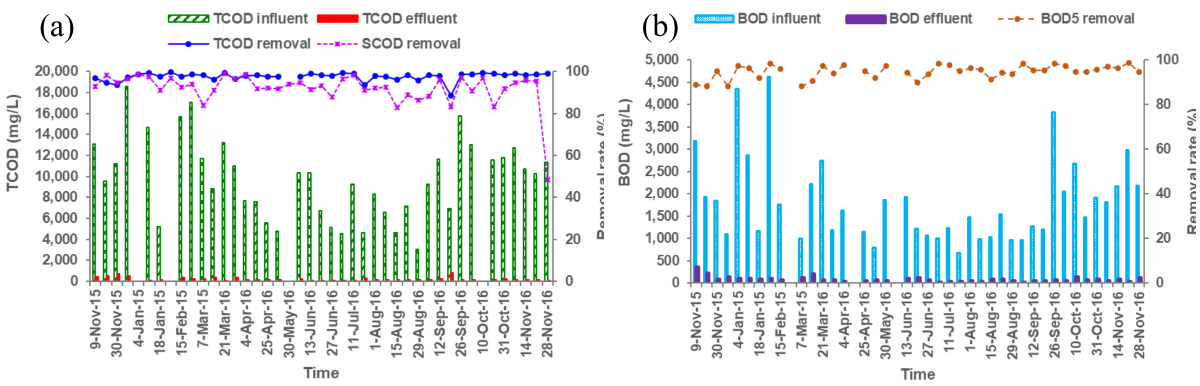

Figure 5 Organic removal efficiency in solar septic tank (a) COD removal, (b) BOD_5 removal.

4) Solid removal

The TS and TVS concentrations of the SST influent varied in the range 4,000–11,000 mg L^{-1} and 3,000–10,000 mg L^{-1}, respectively, and their removal efficiencies are shown in Figure 6 with the TS and TVS reduction being above 91%. The increased temperature in the SST had favorable effects on the reduction of organic matters and generation of well-settleable sludge. Because TS contained in black water is heavy material such as feces or paper which can easily settle. The solids removal efficiencies in septic tanks are usually higher than other parameters. In addition, because the density and viscosity of liquid are inversely proportional to the temperature [16], this phenomena helped to speed up the sedimentation of TS in the SST. Higher temperatures probably caused the liquid density and viscosity to decrease, resulting in better sedimentation of incoming TS and TVS matter. Moreover, since the TS removal efficiency depends on the number of compartments inside the reactor, the installation of the disinfection chamber in the SST could prevent the overflow of small particles. The TVS removal efficiencies were stable at an average of 96%. The high temperature contributed to increased biodegradability of the TVS to methane gas [12].

5) Pathogen removal

Figure 7 reveals 2.2 log reduction of *E. coli* and total coliform in the SST unit. It is obvious that the disinfection chamber with high temperature played an important role in pathogen reduction in the SST system. The high pathogen removal in the SST suggests a potential to reuse the SST effluent in cultivation of perennial crops.

6) Effect of TCOD/TKN ratio on the treatment performance

The box-and-whiskey plots with minimum and maximum values together with the 20, 50 and 70 percentiles of the relationship between TCOD/TKN and the removal efficiency of TCOD and TCOD/TKN and % removal efficiency of BOD_5 are shown in Figure 8(a) and (b), respectively. The removal efficiencies of TCOD and BOD_5 of the SST unit operating at the TCOD/TKN ratio of 25 had highest average values around 98–99%, while the TCOD/TKN ratios resulted in lower TCOD and BOD_5 removal efficiencies, accordingly. The decrease in the TCOD and BOD_5 removal efficiency at the TCOD/TKN ratio more than 25 suggested that a nitrogen deficiency could have limited the microbial/enzyme activities. The TCOD/TKN ratio influenced the treatment performance because of the variation of the amount of carbon causing shifts in the biodegradable pathways, primarily for the conversion of the soluble products. To maintain the C/N ratio of 25 or higher in the black water from the public toilet, using the urine-diverting toilet or adding other sources of the organic material should be considered.

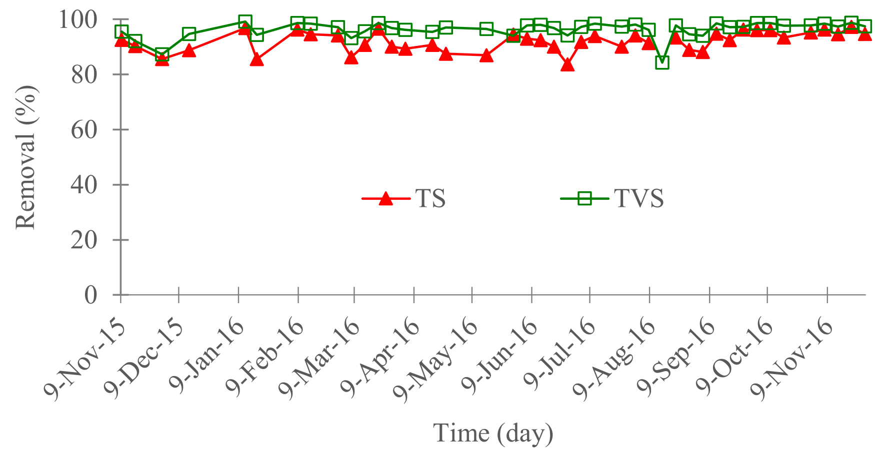

Figure 6 Solid removal efficiency of solar septic tank.

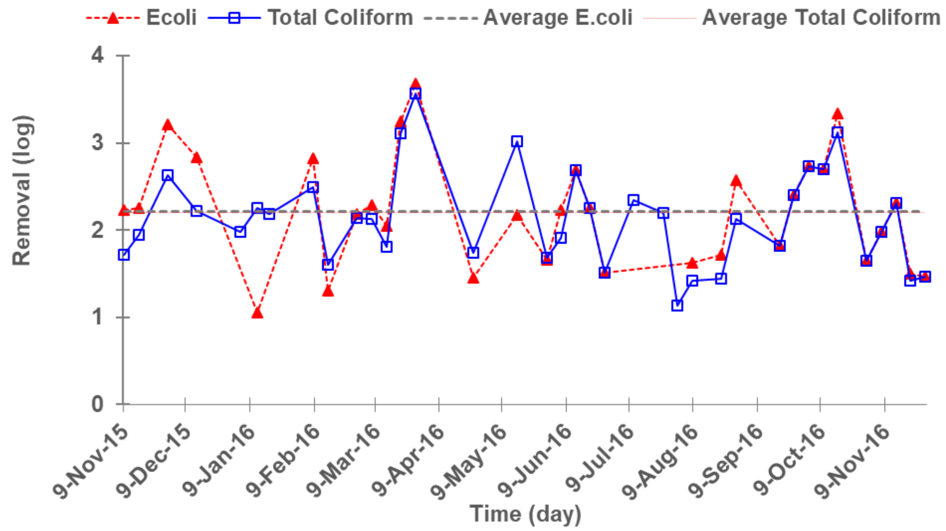

Figure 7 Pathogen removal efficiency of solar septic tank.

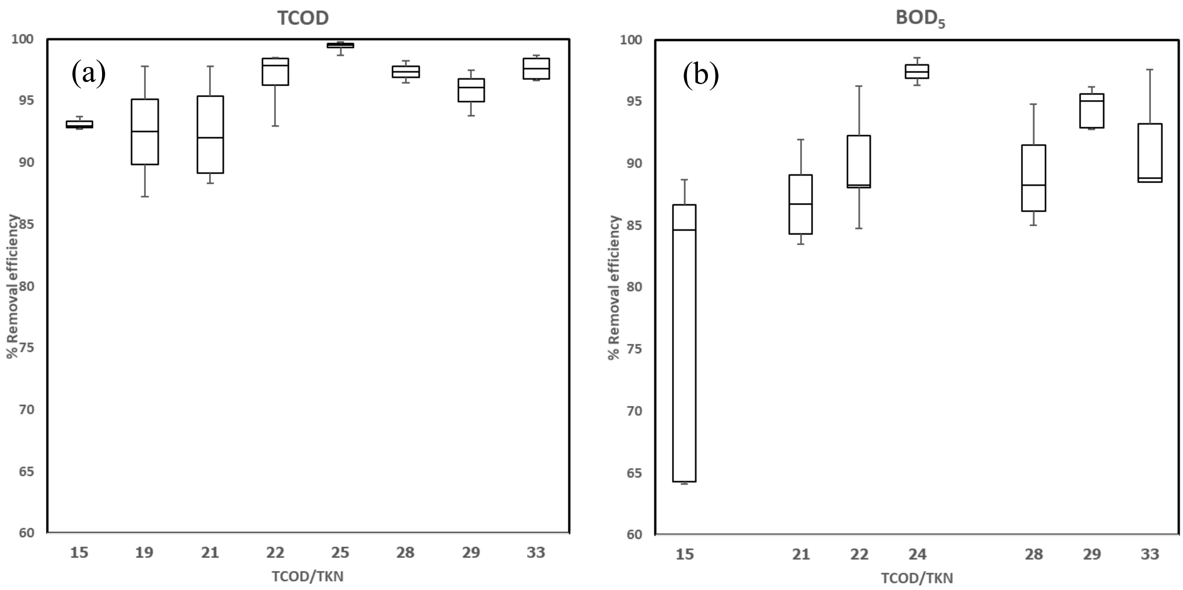

Figure 8 Box-and-whiskey plot of the distribution of the relationship between (a) TCOD/TKN and % removal efficiency of TCOD and (b) TCOD/TKN and % removal efficiency of BOD_5. (no. of sample = 50)

Conclusion

SST is an innovative on-site wastewater treatment technology that uses solar energy to increase temperature inside the septic tank. Innovative and practical techniques to use solar energy in the septic tank are considered as an effective sanitation technology for inactivating pathogens and increasing organic wastes digestion. The results of this study indicated the superior performance of the SST unit in treating black water from the public toilet. Specific conclusions can be made as follows:

1) The pilot-scale SST unit could achieve high removal efficiencies of TCOD, BOD_5, TS, and TVS of 97%, 94%, 91% and 96%, respectively. The inactivation efficiencies of *E. coli* and total coliforms in the solar septic tank were about 2.2 log reduction.

2) The removal efficiencies of TCOD and BOD_5 of the SST unit operating at the TCOD/TKN ratio of 25 had highest average values around 98–99%.

Acknowledgements

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