Research Paper

'*Solar septic tank*': evaluation of innovative decentralized treatment of blackwater in developing countries

Thammarat Koottatep, Stephanie Connelly, Tatchai Pussayanavin, Sopida Khamyai, Wattanapong Sangchun, William Sloan and Chongrak Polprasert

ABSTRACT

An innovative decentralized wastewater treatment system, namely the 'Solar Septic Tank (SST)', was constructed and tested at the household scale in a community in central Thailand. This study aimed to investigate the long-term performance of the SST in treating blackwater subject to year-round variation. Results of the 3-year continuous operation and monitoring showed significant improvement in the SST effluent quality with the potential to minimize environmental problems and public health risks. The SST achieved significantly higher total chemical oxygen demand, soluble chemical oxygen demand, total biochemical oxygen demand (TBOD), soluble biochemical oxygen demand, total kjeldahl nitrogen, total solid and total volatile solid removal efficiencies than a conventional septic tank (CST). The average TBOD concentration of the SST effluent was 150 ± 75 mg/L, meeting the Thai discharge standard (less than 200 mg/L of TBOD), while the average TBOD concentration of the CST was 240 ± 140 mg/L, higher than the Thai discharge standard. The *Escherichia coli* inactivation in the SST was 1–2 log reduction more than that in the CST. The removal efficiencies of TBOD and pathogens exhibited positive correlation with the ratios of the SST temperature.

Key words | blackwater treatment, long-term study, performance evaluation, reinvented toilet technology, Solar Septic Tank, WASH

Thammarat Koottatep
Tatchai Pussayanavin (corresponding author)
Sopida Khamyai
Wattanapong Sangchun
School of Environment, Resources and
    Development,
Asian Institute of Technology,
Pathum Thani,
Thailand
E-mail: *poktatchai@gmail.com*

Stephanie Connelly[†]
William Sloan
School of Engineering,
University of Glasgow,
Glasgow,
UK

Tatchai Pussayanavin
Faculty of Science,
Ramkhamhaeng University,
Bangkok,
Thailand

Chongrak Polprasert
Thammasat School of Engineering,
Thammasat University,
Pathum Thani,
Thailand

[†]Joint first author

HIGHLIGHTS

- To achieve the national discharge standard and the WHO guidelines, 'Solar septic tank (SST)' is proposed.
- SST achieved significantly higher removal efficiencies than the CST.
- Treatment efficiencies between SST and CST during hot and monsoon seasons showed significant difference.
- TBOD removal efficiency and pathogen inactivation of the SST were influenced by the operating temperatures.

INTRODUCTION

More than one billion people in developing countries still lack proper sanitation facilities and access to basic sanitation systems, resulting in more than a million deaths annually due to waterborne diseases (WHO 2017). To achieve the United Nations Sustainable Development Goal 6 (SDG 6) requires urgent action to protect human health and ensure that all people enjoy prosperity by 2030. Water pollution related to sanitation, particularly in developing countries (or low-middle income countries), is a pressing issue directly affecting both public and environmental health (Ryals *et al.* 2019). A principal reason for this problem is the uncontrolled discharge of untreated wastewater. Domestic wastewater management in developing countries usually involves inadequate treatment facilities and lack of proper wastewater treatment system (Areias *et al.* 2020). Centralized wastewater treatment as being practiced in most developed countries is one of the solutions to treat those wastes, but, because of high investment cost and requirement of skilled operation, it seems to be inappropriate for low-middle income countries. Considering the case of Thailand, restricted local budgets or funding, coverage of wastewater treatment plants in many small and isolated villages is still inadequate. Moreover, in developing countries, large capital investment for sewer system and pumping costs is one of the barriers for the construction of centralized wastewater management systems (Massoud *et al.* 2009). In this respect, even existing decentralized or on-site wastewater treatment technologies (such as conventional septic tanks (CSTs) or cesspools) are a better option for developing countries to treat wastewater close to the source. Although the CST does not require a huge budget for installation, it cannot perform effectively to protect human health or environment (Polprasert & Rajput 1982).

Because of the low investment cost and less-complicated installation, since 1995, the government of Thailand has been promoting the application of CST or cesspools as a stand-alone wastewater treatment to treat blackwater or toilet wastewater for new housing or isolated residential/commercial establishments. However, a spatial survey by Koottatep *et al.* (2014a, 2014b) found the treatment efficiencies of the CST to be low (less than 60% removal of organic matter),

and the CST effluent still contained high concentrations of organic matter and pathogens (about more than 200 mg/L of TBOD and 10^6 MPN/100 mL of *Escherichia coli*). The CST effluent has been identified as a major source of surface and ground water pollution in Thailand (Chaiwong *et al.* 2020). Since the CST can be influenced by high sludge accumulation and daily peak flow, direct discharge of effluent with high concentrations of solids, particulate organic matter and also pathogens to the surrounding environment is another potential problem (Gray 2004; Sarathai *et al.* 2010). Thus, these issues require the governments of Thailand and other developing countries to find appropriate solutions for wastewater treatment urgently. Up to the present, there are many reports of pollution and health problems caused by unsanitary managed technology (Heinss *et al.* 1999).

To address the global sanitation problems, the Bill & Melinda Gates Foundation has invested 100 million US$ to reinvent toilet technologies. The Foundation's goals, since 2011, have focused on the development of effective on-site sanitation technologies that poor people can access, and also to create a platform for global sustainability. From this perspective, alternative treatment systems such as the 'Solar Septic Tank (SST)' could be one of the most effective solutions for developing countries (Pussayanavin *et al.* 2015; Connelly *et al.* 2019). The SST is a modified CST with a solar-heated water system to create higher temperature than ambient inside the septic tank. The enhancement of temperature promotes the biodegradation of organic matter and methane formation. Furthermore, temperature also has a significant effect on the settleability and degradation of biological solids and pathogen inactivation (Keating *et al.* 2016; Connelly *et al.* 2017; Polprasert *et al.* 2018). SSTs have been applied for the treatment of blackwater (or toilet wastewater), because they are simple to install and do not require high skill to operate and maintain. At present, there is no scientific evidence to demonstrate the long-term performance of the SST. Thus, the goal of this study was to compare the long-term performance of the SST and CST systems (time-series study) and to determine the systems' capability to operate under variations in tropical temperatures and the change of seasons.

METHODOLOGY

Prototype description

Field testing of an SST and a CST unit was conducted at a housing community in central Thailand (latitude: 13.618795, longitude: 100.530521; Figure 1(e)). The units were tested from 2015 to 2017 (the SST started in operation on May 2015 and the CST started in operation on August 2015) under actual conditions of fluctuating flowrates and climatic conditions (Figure 1(a) and 1(b)). Each experimental unit directly received wastewater from a water-saving toilet with a 3-litre per flush mechanism and served a family of 3–5 people. Figures 1(c) and 1(d) show a photographic view and schematic sketch of the SST and CST. A magnetic counter (OMRON H7EC-N, Japan) was used to measure the number of uses per day, while the daily water usage of each unit was measured using an analog flow meter (GMK, Asahi, Thailand). Ambient temperatures at the test-site were recorded hourly using temperature sensors (PT-100 type HDP/7, SWK Technology, Thailand) installed above the ground. The in-tank temperature of the SST was also recorded hourly using a temperature sensor positioned in the center of the tank.

Both the SST and CST units were made of polyethylene polymer, each with a working volume of 1,000 L (with about 70% of effective volume) in a spherical shape, and received the blackwater (feces, urine and anal cleansing water), while graywater was discharged separately. The SST unit consists of two compartments (Figure 1(a)), while the CST has only one compartment (Figure 1(d)). The first compartment of the SST was designed for solid settling and anaerobic digestion of collected solids (Figure 1(c)). The second compartment, defined as the disinfection chamber, was made of stainless steel (diameter 0.3 m and high 1.2 m) and functions as a polishing unit (Table S1). The disinfection chamber was designed to minimize the effect of short-circuiting from impulse flow and to maintain the temperature in the disinfection chamber more than 40 °C (during daytime), which could simultaneously enhance and inactivate pathogens in the effluent. Temperature difference in the first and second compartments was typically about 5 °C. Temperatures of the SST were increased by circulating hot water generated from a 6 m^2 solar water heating device

through a heat exchanger copper spiral; the hot water was pumped through the heat exchange system at a rate of 5 L/min. A sensor in the hot water storage tank and an electric-circuit controller were used to control the flow circulation when the temperature of the hot water storage tank reached the target of 50 °C or more.

Performance evaluation

Influent and effluent samples were collected bi-weekly during the first year and monthly during the second and third years to obtain key physical and chemical monitoring data of the system performance. The influent and effluent samples were collected in sealed buckets; for the influent samples, the inflow to the septic tanks was disconnected via a sampling valve for a period of 24 h. Physical and chemical (total chemical oxygen demand (TCOD), soluble chemical oxygen demand (SCOD), total biochemical oxygen demand (TBOD), soluble biochemical oxygen demand (SBOD), total kjeldahl nitrogen (TKN), total solid (TS) and total volatile solid (TVS)) and bacteriological parameters (*E. coli*) were analyzed according to the standard methods (APHA 2017). Open source R software was used for statistical analyses and graphics of this study. Statistical difference (at a 95% confidential level) of the relationship between the treatment units and its efficiencies was done by analysis of the variance (ANOVA), and comparing the multiple means was assessed using post-hoc test (Tukey's Honest Significant Difference (HSD)). The time-series plots were used in developing the local polynomial regression to build up a generalization of moving average (in line), a function that describes the deterministic part of the variation in the data. Treatment performance of the SST and CST was evaluated based on removal efficiency (RE) shown in the following equation:

$$\text{Removal efficiency (RE)} = \frac{(Si - Se)}{Se} \times 100 \tag{1}$$

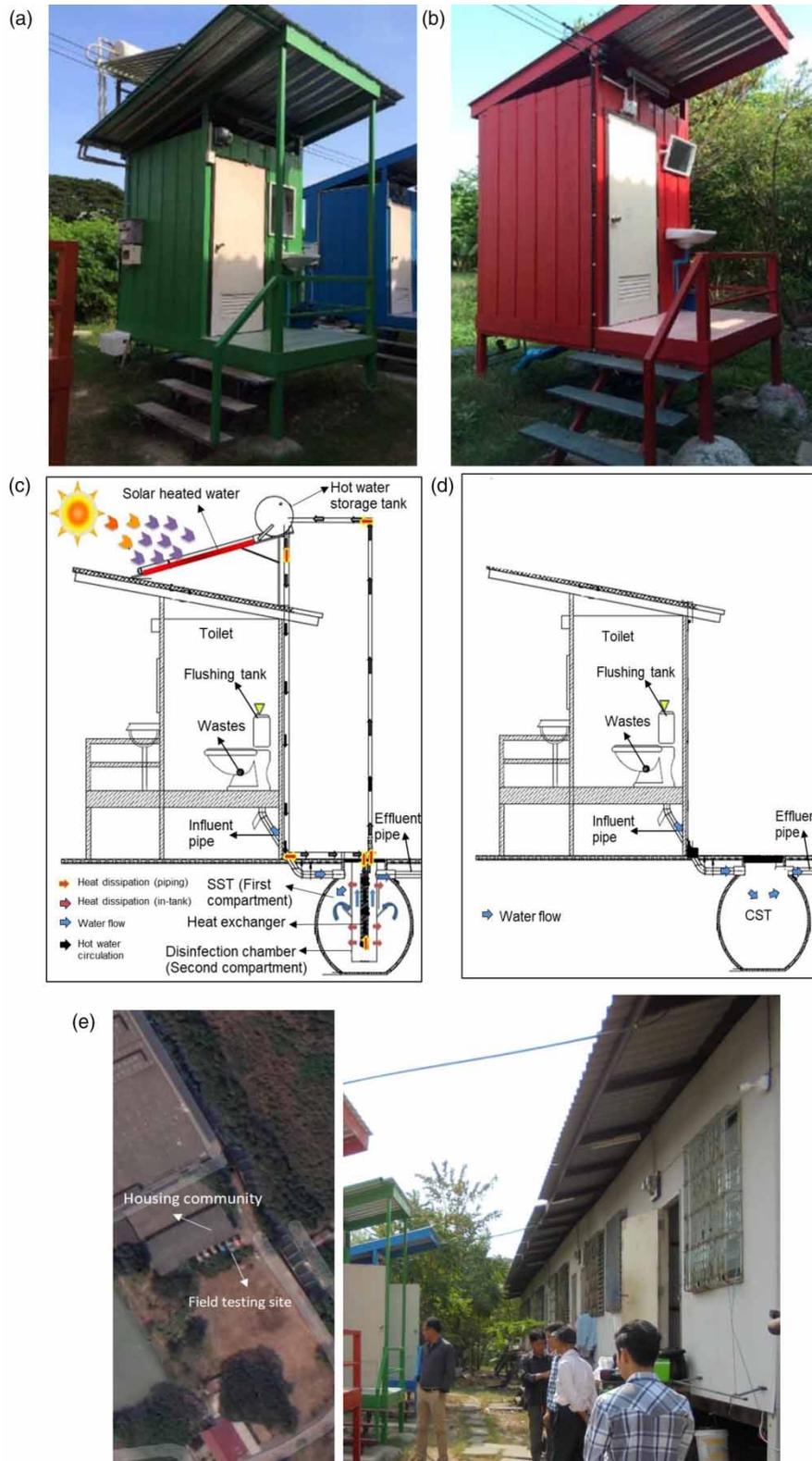where Si is the concentration in influent (mg/L) and Se is the concentration in effluent (mg/L).

Figure 1 | Field testing of SST (a), field testing of CST (b), schematic configuration of SST (c), schematic configuration of CST (d) and testing site: housing community in central Thailand (e).

RESULTS AND DISCUSSION

System operation

The climate in Thailand is considered to be in the 'tropical range', the temperature at the daytime is greater than 36 °C and in the night-time the temperature is dropped to 31 °C. The average yearly ambient temperatures were found to have a steadily increasing trend during the operation period from 2015 to 2017, depending on the annual climatic conditions.

The temperature profile of the SST over the course of the experiment is presented in Figure 2, and the calculated mean in-tank temperature over the course of the study was 41 ± 4.0 °C which was satisfactory for the thermophilic condition. It is obvious from Figure 2 that the average SST temperature was between 41.5 ± 4.5 in the daytime and 40.3 ± 3.1 in the night-time. The performance of the solar system was effective in daytime and sufficient to maintain temperature in the night-time (Figure 2(a)). The difference in daytime and night-time temperatures of the SST was between 1 and 2 °C, which should not have much effects on the microbial activities inside the tank.

Operation of the SST and CST units was commenced in 2015 by feeding the blackwater without additional inoculation, i.e., the systems were seeded from the microbes present in the blackwater entering the system only. The average values of wastewater flow and number of users were found in the same magnitude of about 98.8–110.0 L/d and 17–23 persons, respectively.

The influent TCOD, SCOD, TBOD, SBOD, TKN, TS, TVS and *E. coli* concentrations of the CST unit were $1,618 \pm 810$ mg/L, 494 ± 182 mg/L, 643 ± 289 mg/L, 74 ± 139, 295 ± 95, $1,556 \pm 646$, 943 ± 471 mg/L and 9.7×10^8 MPN/100 mL of *E. coli*, respectively. A similar trend was noticed for influent concentrations of the SST units which were $3,834 \pm 2,828$ mg/L of TCOD, 879 ± 495 mg/L of SCOD, $1,131 \pm 725$ mg/L of TBOD and 399 ± 183 mg/L of SBOD, 463 ± 218 mg/L of TKN, $3,046 \pm 1,659$ mg/L of TS, $2,351 \pm 1,450$ mg/L of TVS and 1.1×10^8 MPN/100 mL of *E. coli*. The influent blackwater quality (Table S1) was within the range of 'high strength' wastewater. In general, there was high variation of pollutant concentrations in the blackwater, depending on the user behavior and characteristic of feces, urine and toilet paper.

The operating conditions of the SST and CST from the field data are as shown in Supplementary Material, Table S1.

System performance

Effluent concentrations of TCOD, SCOD, TBOD and SBOD in the SST were consistently lower than those of the CST, particularly during the first 4 months of operation, indicating that heating the system enabled considerably more effective treatment during start-up of new SST unit than the new CST systems. The removal efficiencies of TCOD and TBOD (Figure 3(a) and 3(b)) of the SST and the CST units improved over time and increased to above 80% after 180 days of operation. In addition to promoting pathogen inactivation and minimizing short-circuiting, the disinfection chamber installed in the SST was hypothesized to serve as a polishing unit, contributing to the removal of residual pollutants. Indeed, it was observed that during the 3 years of continuous operation, the SST unit yielded significantly better performance (ANOVA, $p < 0.05$) for each of the parameters monitored (Figure 3). The SST performed with average treatment efficiencies of $88 \pm 9\%$ for TCOD removal and $83 \pm 13\%$ for TBOD removal, more effective than the treatment performance of the CST unit which were 61 ± 24 and $58 \pm 28\%$, respectively, resulting in the effluent TCOD and TBOD concentration of 534 ± 216 and 240 ± 140 mg/L, respectively (Figure 3). These data demonstrate that the performance of the SST for TCOD, SCOD, TBOD and SBOD removal was typically 20–30% ($p < 0.05$) better than that of the CST and that the removal efficiencies were generally more stable over time. The greater variability in RE and discharge quality in the CST was probably affected by the hydraulic and impulse loads, and that operation in the absence of heating resulted in a lower amount of active biomass responsible for the biodegradation of organic matter. In spite of fluctuation in the operating temperatures (Figure 2), the effluent characteristics from the SST (mean ± SD of 310 ± 115 mg/L of TCOD, 160 ± 60 mg/L of SCOD, 150 ± 75 mg/L of TBOD and 60 ± 20 mg/L of SBOD) were relatively stable (Figure 3(a) and 3(b)), and, importantly, frequently satisfy the discharge
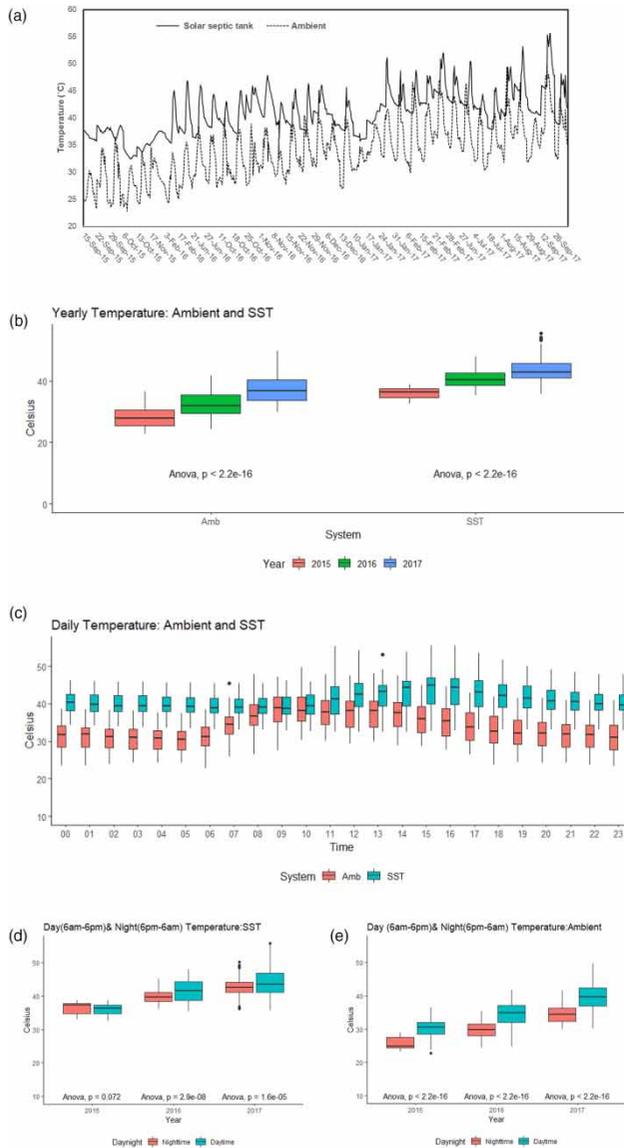
Figure 2 | Temperatures of SST and ambient (Amb). (a) In-tank temperature of SST and ambient temperature (time-series). (b) Average yearly temperature. (c) Daily temperature profile. (d) Yearly daytime (6 am to 6 pm) and nighttime (6 pm to 6 am) temperature: SST. (e) Yearly daytime (6 am to 6pm) and nighttime (6 pm to 6 am) temperature: Amb.

standards of Thailand (MNRE 2010). It is noted, however, that the effluent TBOD concentrations during the monsoon season or cloudy conditions were occasionally above the discharge standards even for the SST.

While mean removal rates were significantly higher in the SST than the CST, the mean effluent TKN concentrations of the CST and SST (Figure 3(c)) were observed to be in the same magnitude of about 100–400 mg/L,

respectively. The mean TS and TVS removal efficiencies of the SST were 71 and 85%, respectively, significantly higher ($p < 0.05$) than those of the CST which were 32 and 52%, respectively. Thus, the CST was found to be less effective in solid sedimentation than the SST. It could be hypothesized that higher temperatures in the SST reduced the liquid density and viscosity, resulting in better sedimentation of the influent TS and TVS.

The heated chamber in the SST targets coliform reduction by partial pasteurization, resulting in the SST more 1–2 log of *E. coli* inactivation than in the CST (Figure 3). The statistical test revealed that the *E. coli* inactivations differ significantly between the SST and CST ($p < 0.05$). It was observed, however, that the *E. coli* inactivation in both the SST and CST units was influenced by the drop in temperature or daily temperature variation during the monsoon season.

Figure 4 compares the treatment performance of the SST and CST during two different seasons, i.e. hot (November to April) and monsoon (May to October). Tukey's HSD analysis was performed for each performance parameter to determine the statistical significance of seasonal difference in the performance of each system during each season at 95% confidence interval using R program. While seasonal effects were observed in each system, the analysis demonstrates that in each season (the ratio of SST:CST in the monsoon season and SST:CST in the hot season), the SST performed significantly better than the CST for most of the parameters (except that TCOD was found be insignificant ($p > 0.05$) between the SST and CST). The results presented in Figure 5 show a clear evidence that the treatment efficiencies of SCOD, TBOD, SBOD, TKN, TS and TVS of the SST were higher than those of the CST and significantly different from the hot and monsoon seasons.

The removal efficiencies of the SST and CST of the five main important parameters, namely TCOD (SST_TCOD and CST_TCOD), TBOD (SST_TBOD and CST_TBOD), SCOD (SST_SCOD and CST_SCOD), TKN (SST_TKN and CST_TKN) and *E. coli* log reduction (SST_*E. coli* and CST_*E. coli*), were further evaluated by analyzing the yearly relationship between operational conditions of the wastewater flow (SST_flow and CST_flow), the average of SST temperature (SST_average_temp), the average of SST daytime temperature (SST_average_daytime_temp), the ambient temperature (Amb_Average_Temp) and the
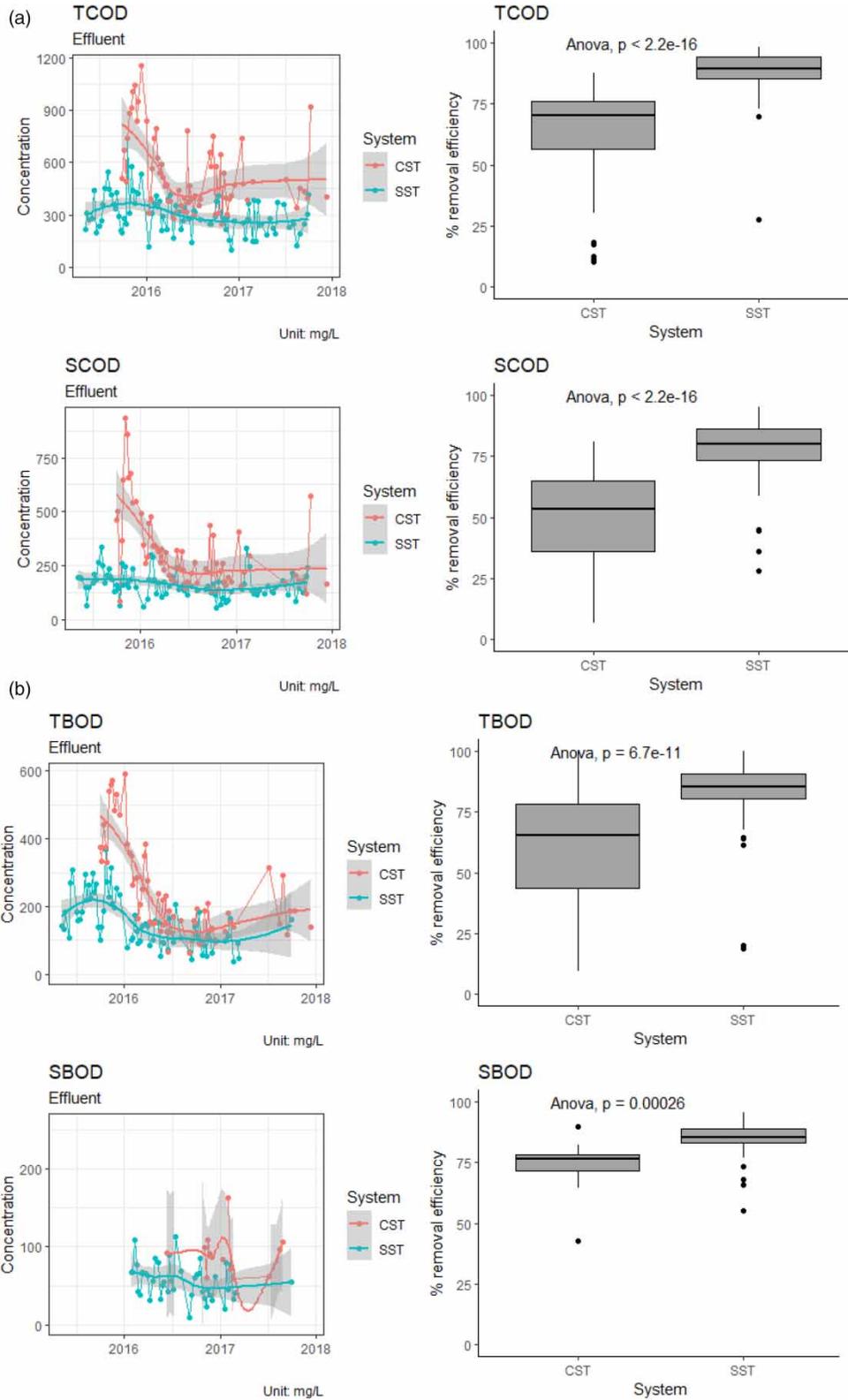
Figure 3 | Treatment performance of SST and CST: (a) COD, (b) BOD, (c) TKN, (d) TS and TVS, and (e) *E. coli*. *(continued.).*
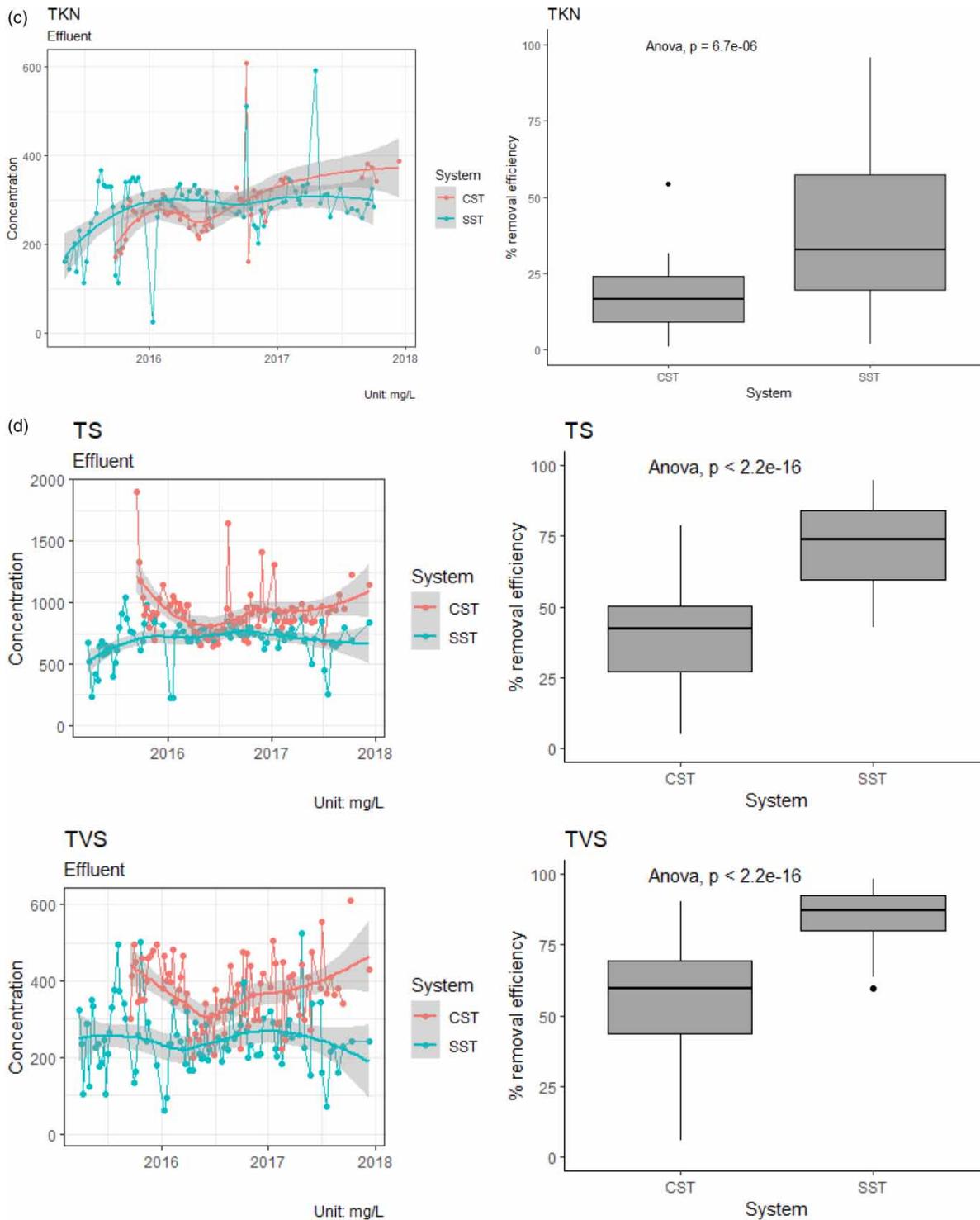
Figure 3 | Continued.

daytime ambient temperature (Amb_Average_Daytime_Temp) during the operation of the system, which could exhibit the influence between these parameters and system performance

(Figure 5). The results indicated that there were high positive correlation values (corr) between the SST temperature (SST_Average_temp and SST_Average_Daytime_Temp) for
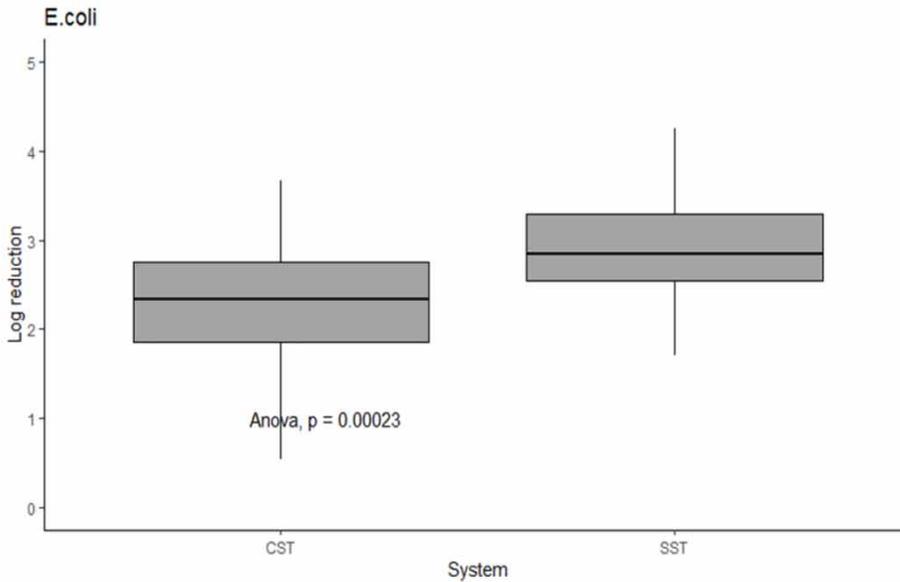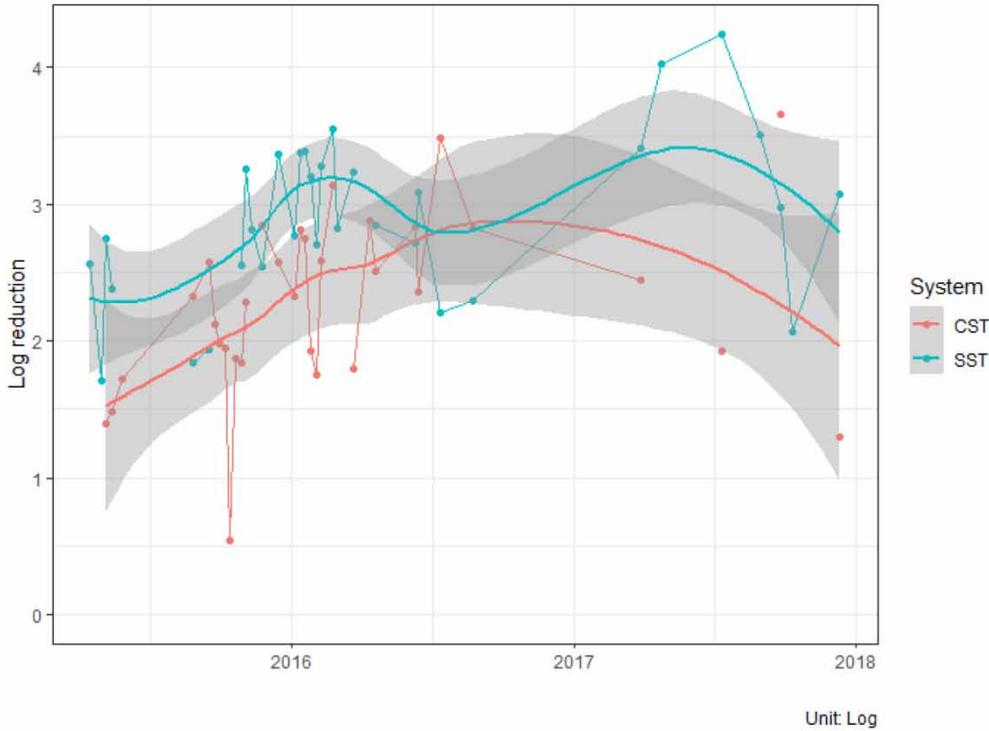
Figure 3 | Continued.

TBOD (0.992 and 1, respectively) and *E. coli* log reduction (0.9725 and 0.9079, respectively) of SST, and the correlations between the ambient temperature (Amb_Average_temp and Amb_Average_Daytime_Temp) and TCOD, SCOD and TBOD of CST were found in high correlation values ranging between 0.8939 and 0.9253. For the relationships between
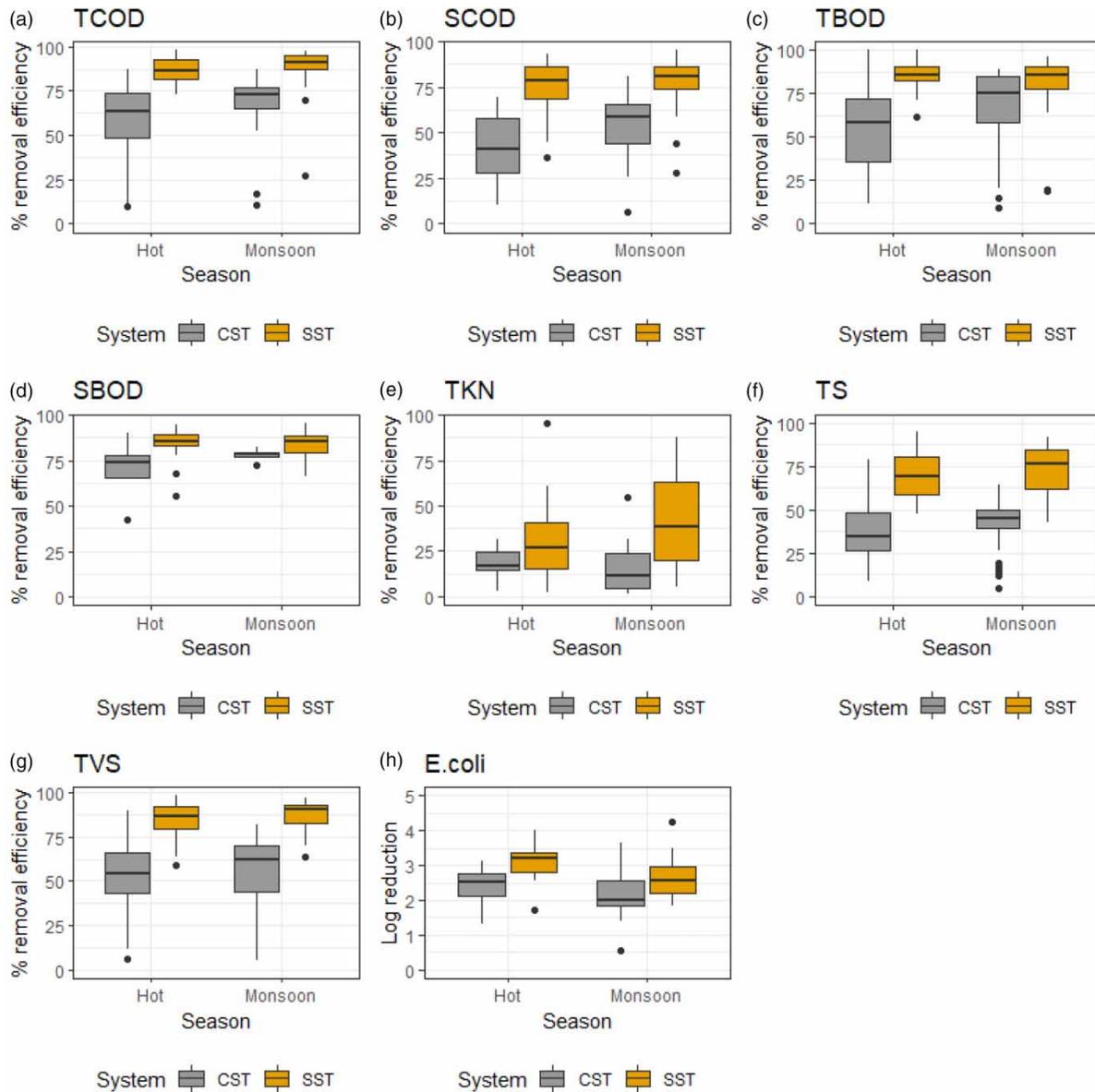
Figure 4 │ Comparison of treatment performance during hot and monsoon seasons.

wastewater flow and removal efficiencies, the SCOD and TKN removal efficiencies of the SST were high correlation values, while weak relationships between wastewater flow and TCOD, SCOD, TBOD, TKN and *E. coli* were observed. It seems that the TBOD RE and pathogen inactivation of the SST and TCOD, SCOD and TBOD removal efficiencies of the CST were mainly influenced by the operating temperatures.

For the prototype of a single family, the SST system was estimated to cost about US$ 740 (or about 28% of the total cost), while the commercial solar-heated water with other accessories (electric-circuit controller and circulating pump) would cost about US$ 1,840 (72%), or the total investment of the integrated system would be in the range of US$ 2,580. However, it should be noted that the field test (or prototype unit) should thus be an integral part of
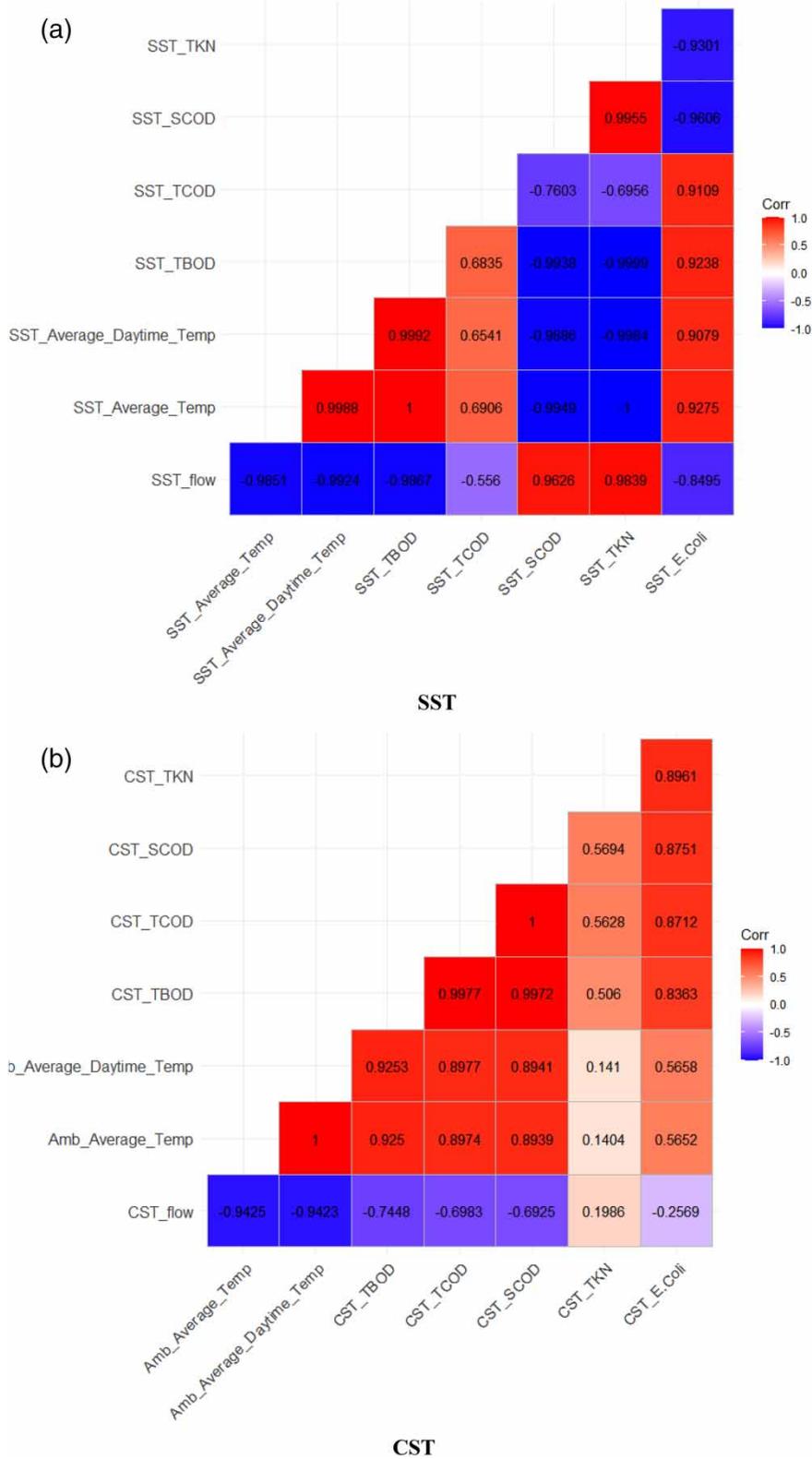
Figure 5 | Relationships between operational conditions (temperature and daytime temperature and wastewater flow) and removal efficiencies of SST and CST, (a) SST, (b) CST (correlation coefficient with a unit-free measure ranges from −1 to +1).

the design process and not be used only to consider as a final product and the commercialized product.

CONCLUSIONS

The results of this study demonstrated the SST to be an effective on-site treatment technology in reducing organic–chemical, solid pollutants and *E. coli* from the blackwater. During the 3 years of continuous operation, the SST unit could achieve the treatment efficiencies of $88 \pm 9\%$ for TCOD and $83 \pm 13\%$ for TBOD, and the SST had TCOD, SCOD, TBOD and SBOD removal efficiencies in the range of 20–30% higher than the CST. Furthermore, at the mean operating temperature of 42 °C, the SST effluent characteristics typically achieved discharge standards of Thailand, although occasional failures were observed during the monsoon season. The treatment efficiencies of the SST during the hot and monsoon seasons were consistently significantly better than those of the CST. The operating temperature of the SST had a high positive correlation values (corr) with TBOD (0.992 and 1, respectively) and *E. coli* log reduction (0.9725 and 0.9079, respectively).

ACKNOWLEDGEMENTS

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

American Public Health Association/American Water Works Association/Water Environment Federation 2017 *Standard Methods for the Examination of Water and Wastewater*, 23rd edn. APHA/AWWA/WEF, Denver, CO.

Areias, I. O. R., Vieira, C. M. F., Colorado, H. A., Delaqua, G. C. G., Monteiro, S. N. & Azevedo, A. R. G. 2020 Could city sewage sludge be directly used into clay bricks for building construction? A comprehensive case study from Brazil. *Journal of Building Engineering* **31**, 101374.

Chaiwong, C., Koottatep, T. & Polprasert, C. 2020 Comparative study on attached-growth photobioreactors under blue and red lights for treatment of septic tank effluent. *Journal of Environmental Management* **260**, 110134.

Connelly, S., Shin, S. G., Dillon, R. J., Ijaz, U. Z., Quince, C., Sloan, W. T. & Collins, G. 2017 Bioreactor scalability: laboratory-scale bioreactor design influences performance, ecology, and community physiology in expanded granular sludge bed bioreactors. *Frontiers in Microbiology* **8**, 664.

Connelly, S., Pussayanavin, T., Randle-Boggis, R. J., Wicheansan, A., Jampathong, S., Keating, C., Ijaz, U. Z., Sloan, W. T. & Koottatep, T. 2019 Solar septic tank: next generation sequencing reveals effluent microbial community composition as a useful index of system performance. *Water* **11** (12), 2660.

Gray, D. M. D. 2004 *Pathogen Destruction Efficiency In High Temperature Digestion*. IWA, UK.

Heinss, U., Larmie, S. A. & Strauss, M. 1999 *Characteristics of Faecal Sludges and Their Solids-Liquid Separation*. EAWAG/SANDEC, Rio de Janeiro, Brazil.

Keating, C., Chin, J. P., Hughes, D., Manesiotis, P., Cysneiros, D., Mahony, T., Smith, C. J., McGrath, J. W. & O'Flaherty, V. 2016 Biological phosphorus removal during high-rate, low-temperature, anaerobic digestion of wastewater. *Frontiers in Microbiology* **7**, 226.

Koottatep, T., Eamrat, R., Pussayanavin, T. & Polprasert, C. 2014a Hydraulic evaluation and performance of on-site sanitation systems in Central Thailand. *Environmental Engineering Research* **19** (3), 269–274.

Koottatep, T., Phuphisith, S., Pussayanavin, T., Panuvatvanich, A. & Polprasert, C. 2014b Modeling of pathogen inactivation in thermal septic tanks. *Journal of Water, Sanitation and Hygiene for Development* **4** (1), 81–88.

Massoud, M. A., Akram, T. & Nasr, J. A. 2009 Decentralized approaches to wastewater treatment and management: applicability in developing countries. *Journal of Environmental Management* **90**, 652–659.

Ministry of Natural Resources and Environment of Thailand: MNRE 2010 *Definition of Standard of Wastewater Discharge From Domestic Wastewater Treatment Plant in Thailand*. Royal Thai Government, Thailand.

Polprasert, C. & Rajput, V. S. 1982 *Septic Tank and Septic Systems*. Environmental Sanitation Reviews. Environmental Sanitation Information Center. Asian Institute of Technology, Thailand.

Polprasert, C., Koottatep, T. & Pussayanavin, T. 2018 Solar septic tanks: a new sanitation paradigm for Thailand 4.0. *ScienceAsia* **44**, 39–43.

Pussayanavin, T., Koottatep, T., Eamrat, R. & Polprasert, C. 2015 Enhanced sludge reduction in septic tanks by increasing temperature. *Journal of Environmental Science and Health, Part A* **50**, 1–9.

Ryals, R., McNicol, G., Porder, S. & Kramer, S. 2019 Greenhouse gas fluxes from human waste management pathways in Haiti. *Journal of Cleaner Production* **226**, 106–113.

Sarathai, Y., Koottatep, K. & Morel, A. 2010 Hydraulic characteristics of an anaerobic baffled reactor as onsite wastewater treatment system. *Journal of Environmental Sciences* **22** (9), 1319–1326.

World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) 2017 *Progress on Drinking Water, Sanitation and Hygiene 2017 Update and SDG Baselines*. Available from: http://www.unwater.org/publications/whounicef-joint-monitoring-program-water-supply-sanitation-hygiene-jmp-2017-update-sdg-baselines/.