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# On-site domestic wastewater treatment system using shredded waste plastic bottles as biofilter media: pilot-scale study for effluent standard in Bhutan

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## Abstract:

In this study, a 1,000 L/d capacity one-off on-site wastewater treatment system was operated for over a year as a pilot alternative to the conventional on-site treatment as currently used in urban Bhutan. An up-flow anaerobic sludge blanket (UASB) was used for blackwater treatment (to replace "septic tank followed by an anaerobic biofilter (ABF) (to replace soak pits) for the treatment of a mixture of greywater and UASB effluent. Shredded waste plastic bottles were used as the novel biofilter media in the ABF. During a yearlong operation, the pilot system produced a final treated effluent from ABF with average BOD 5 28 mg/L, COD 38 mg/L, TSS 85 mg/L and 5 log units of *Escherichia coli* These effluents meet three out of four of the national effluent discharge limits of Bhutan, but unsuccessful to meet the *Escherichia coli* standard over a yearlong operation. Further process optimisation may enable more significant *Escherichia coli* removal. An economic analysis indicates that the total unit cost (capital and operating expenditures) of this alternative wastewater treatment system for more than 50 users ranges between USD 0.27 - 0.37/person/month comparable to USD 0.29 - 0.42/person/month for the current predominant on-site system, i.e., “septic tanks”. This pilot study, therefore, indicates that this wastewater treatment system using shredded waste plastic biofilter media has high potential to replace the current conventional treatment, i.e., “septic tanks”, which are often overloaded with grey water and discharging effluent which does not meet the national standards.

**Keywords:** ABF, domestic wastewater, on-site sanitation, plastic wastes, pollution, UASB

## 1. Introduction

Providing safe drinking water and improved sanitation facilities is listed under the Goal 6 (clean water and sanitation) of the UN Sustainable Development Goals to safeguard public health and well-being while at the same time protecting and restoring water-related ecosystems (UN 2017). Conventional activated sludge processes are the most widely adopted treatment technology in the world for human faeces (Tchobanoglous 2014). However, most recently, aerobic granular sludge processes have been gaining significant interest because of their compactness and greater cost-effectiveness (Nancharaiah & Sarvajith 2019). However, these mainstream treatment technologies are still capital and energy-intensive (Hahn & Figueroa 2015), making them less affordable for most developing countries. Anaerobic treatment of municipal wastewater is considered to be the most sustainable because this treatment approach requires no or very little energy to operate and generates energy in the form of biogas (Verstraete, Van de Caveye & Diamantis 2009). Anaerobic processes for municipal wastewater treatment with biogas generation are commonly adopted in tropical and sub-tropical regions for waste with chemical oxygen demand (COD) removal ranging from 40 - 75% (Heffernan, Van Lier & Van Der Lubbe 2011). However, anaerobic treatment technology is not yet investigated in temperate climates such as Bhutan. Simple anaerobic bioreactors such as ABF using local wastes or biofilters provide a long solid retention time (SRT) decoupled from hydraulic retention time (HRT) which facilitates low-temperature treatment of wastewater.

At the same time, plastic waste has become a global problem and has also been growing in Bhutan over the years. Plastic makes up 13% of the municipal solid waste in Bhutan (Phuntsho et al. 2010) accounting for 40.3 tonnes per day of total municipal waste generated in the capital Thimphu alone (RGOB 2019), which is a significant waste for a small country like Bhutan. The problem in Bhutan is also deteriorated by the absence of industries to recycle waste plastic, and road transportation to India via mountainous terrain has proven to be expensive. As a result, waste plastic bottles are dumped into landfills, posing significant environmental risks as harmful leachates as well as taking up valuable landfill capacity. Recently in 2019, there has been a trial in Bhutan to use plastic wastes as a road surfacing material for paved roads to reduce the need for expensive fossil fuel-based bitumen usually used as road surfacing binder. Other innovative solutions are required to reuse plastic wastes to minimise the mounting non-biodegradable waste problem in Bhutan.

Bhutan has experienced rapid urbanisation, putting enormous pressure on the government to meet demands for urban infrastructure and services including for improved urban sanitation. With limited government resources, providing a public sewerage system to all urban centres as is the current policy goal will be a significant challenge. Our recent study observed that over 80% of the towns in Bhutan rely on conventional on-site sanitation treatment systems, i.e., “septic tanks” to dispose of their domestic wastewater (Dorji et al.

2019). One of the major concerns is that about 40% of this on-site treatment was found to be inadequate due to omission of the sub-soil treatment phase due to lack of space in the urban areas. Instead, effluent is allowed to flow into surface drains, posing a significant risk to public health. Furthermore “septic tanks” are only designed to treat blackwater. At the same time, the greywater is discharged openly to surface drains or is directed into septic tanks compromising their anaerobic function as well as leading to overflow events.

Recognising the need for an alternative on-site treatment that addresses all the issues and challenges in unsewered areas of urban Bhutan, a novel on-site domestic wastewater treatment system was evaluated through a lab-scale study (Dorji et al. 2021). The on-site treatment system consisted of a UASB for primary treatment of blackwater (BW) as an alternative to the “septic tank”, followed by an ABF to treat combined primary effluent from UASB and household greywater (GW). The ABF was packed with shredded waste plastic bottle flakes as the biofilter media. This lab-scale study using synthetic wastewater revealed that a combined UASB and ABF process using shredded waste plastic bottles as biofilter media could be an effective on-site treatment system for domestic wastewater (Dorji et al. 2021). Shredded plastic bottles were selected as biofilter media because they are readily available in Bhutan, have been found to be effective biofilter media due to the large surface area to volume ratio, high mass transfer efficiency as media due to their lightweight, the possibility of greater depth of construction (Dacewicz & Chmielowski 2018) in addition to its long life. Also, plastics have a low density and more excellent specific surface when compared to gravel and other conventional biofilter media (do Couto et al. 2015).

UASB reactors have a simple design, low capital and operating costs while providing better retention of solids compared to other anaerobic reactors (Bal & Dhagat 2001). UASB reactors are often described as “improved septic tanks”, having better treatment efficiency due to the development of a sludge bed which behaves like a physical media, trapping the active biomass under an up-flow hydraulic regime (Coelho et al. 2004). The passage of wastewater through the height of the sludge blanket allows for natural separation of microorganisms that perform the biochemical steps of hydrolysis, acidogenesis, acetogenesis, and methanogenesis, converting the complex organics into biogas comprising mostly $CH_4$ and $CO_2$ (Alptekin 2008; Hahn & Figueroa 2015; Mahmoud et al. 2004). UASB reactors can handle large volumes of biosolids without clogging, with sound biogas generation and collection from the gas-liquid-solid-separator (GLSS) (Haandel, Catunda & Lettinga 1996). However, UASB provides only primary treatment of BW and requires further treatment for the removal of organics remaining in the effluent. For the secondary treatment of the UASB effluent, ABFs appear to be suitable due to their cost-effectiveness, and recycling of filter materials used in two-step treatment systems for developing countries (Chernicharo & Machado 1998).

The objective of this study is, therefore, to conduct a long-term field operation and performance demonstration of a full-scale pilot on-site wastewater treatment plant for the treatment of both BW and GW in Bhutan. The outcomes of this pilot study could provide scientific evidence for policymakers in Bhutan to recognise and promote alternative technology options to address environmental pollution from poorly maintained on-site sanitation and treatment. This pilot on-site wastewater treatment system consisted of a UASB and ABF filled with shredded waste plastic bottles connected to treat domestic wastewater generated from a residential building. Much of the previous research on UASBs or ABFs at low temperature has been done at a much smaller scale using smaller reactor sizes of less than 25 L (Uemura & Harada 2000), short-term operation and usually treating synthetic wastewater (Mahmoud et al. 2004). To the best of our knowledge, there has been no report until now on the pilot-scale study using waste plastic flakes as biofilter media for a real domestic wastewater treatment including greywater treatment although the treatment processes such as UASB and biofilter itself are already well established. This study will also be the first-ever pilot-scale on-site wastewater treatment technology demonstration in Bhutan.

## 2. Materials and Methods

### 2.1 Location and description of the pilot site

The pilot site is located at 26° 50’59.33” N, 89° 23’ 48.96” E within the campus of the College of Science and Technology (CST), Rinchending, Bhutan, at an elevation of 1600 m above the sea level and 5 km from Phuentsholing, the second-largest city in Bhutan, bordering the Indian State of West Bengal. A sultry, humid subtropical climate characterises this area with summer (June - August) mean minimum temperature of 18.0 - 25.3$^{o}$C and mean maximum temperature of 29.1 - 34.7°C in the last ten years (2008 - 2017). The winter (December - February) is colder with a mean minimum temperature of 9.4 - 21.7°C and mean maximum temperature of 22.9 - 30.8°C (NCHM 2018). The annual rainfall recorded between 2008 and 2017 ranged between 1,681 - 4,979 mm (NCHM 2018). **Figure 1** shows the location of the pilot shed within the CST campus.

### 2.2 Set-up of the pilot on-site wastewater treatment system

The pilot on-site wastewater treatment system consisted of two anaerobic bioreactor tanks: a UASB followed by an ABF connected in series and housed inside a closed shed located below two CST staff buildings of 12 household units. Both the bioreactors were made from fibre reinforced glass each with a hydraulic volume of 595 L (2 m high and 0.6 m diameter) with a wall thickness of 4 mm. The base of the reactors was cone-shaped resting on the plain cement concrete for easy desludging. Chlorinated polyvinyl chloride (CPVC) pipes and fittings were used for the inflow and outflow of wastewater. A stainless steel deflector and gas-liquid-solid separator (GLSS) were placed on the top portion of the UASB reactor (refer to **Figure 1**). A mild steel weir was used in the ABF treated with anti-corrosive paint. Inside the bottom of the ABF, rectangular CPVC pipes formed a pipe grid with holes drilled on the underside (to prevent clogging of pores with sludge) was constructed for "sparged" distribution of the influent. The reactor design of UASB and ABF was based on a previous lab-scale study which had identified optimum HRTs: 2-d HRT for UASB treating blackwater and 8.8 hours for ABF treating mixed UASB blackwater effluents and greywater (Dorji et al. 2021).

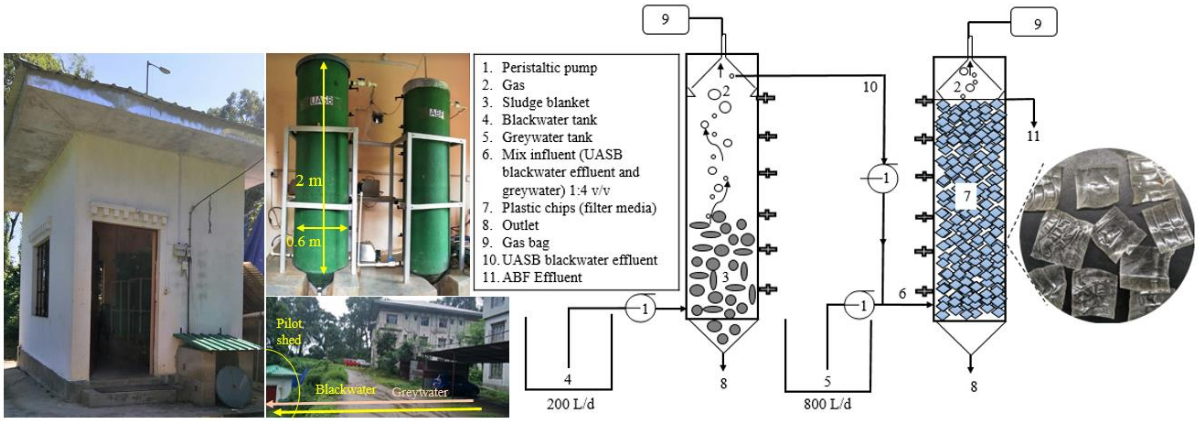


**Figure 1**: Schematic diagram of UASB-ABF pilot system with roughened plastic filter media.

The pilot on-site wastewater treatment system was designed for a total capacity of 1000 L/d, assuming 200 L/day of blackwater and 800 L/day of greywater for 10 persons or about two household units, considering 100 L/p/d wastewater generation, consisting of 20 L/p/d of BW and 80 L/p/d GW.

A small portion of the BW from the residential buildings that currently goes to an existing “septic tank” was diverted to the BW balance tank (200 L plastic tank) from where it was then pumped to the UASB reactor using a peristaltic pump (Lead Fluid, China) set at a fixed flow rate of 139 mL/min (200 L/d). Although in a real-life application, the wastewater can be gravity fed to the bioreactors or placed underground from a reservoir tank using non-return valves, pumps were used in this study to control the flow rates going to each bioreactor. The balance tank also served as a pre-treatment in removing heavier grit, large objects (installed screen mesh of 5 mm x 5 mm) and was fitted with a stirrer (DLH Overhead Stirrer VELP Scientifica, Italy) to achieve proper mixing of the BW and to break up faecal solids to prevent choking of pipes and peristaltic pumps. An overflow pipe in the BW balance tank ensured that the detention time did not exceed 0.25 d to avoid odour issues. An outlet from the sloping bottom of the tank was provided to flush out any settled grit and excess solids under gravity. The overflow from the BW balance tank was sent to the make-shift “septic tank” from where the final effluent was then disposed using a soak-pit filled with broken bricks, providing further soil treatment.

Currently, the GW (from kitchens, bathrooms and laundries) from the buildings is simply discharged into surface water drains. A new 100 mm diameter CPVC pipe was installed to collect GW from the building and sent to the pilot treatment plant. The GW was first collected in a GW balance tank (500 L plastic tank) from where it was then pumped to the ABF reactor with the help of a peristaltic pump (Lead Fluid, China). The overflow system of the GW balance tank was adjusted to have as short hydraulic detention time as possible (0.125 d in this case) and the overflowing GW was sent to the make-shift “septic tanks” for final disposal. The sloped bottom of the balance tank contained an outlet to flush out any settled heavy grit and solids. **Figure 1** shows the process diagram of the pilot on-site wastewater treatment system adopted in this work.

The ABF reactor was filled with 46 kg of waste plastic bottles flakes as biofilter media as presented in **Figure 1** with a total reactor hydraulic volume of 595 L. Waste plastic bottles were collected from Phuentsholing City municipality, cleaned and manually cut into flake sizes of about 40 mm x 40 mm since no shredding equipment is available. Although, in our earlier lab-scale study, the largest plastic flake size used was 30 mm x 30 mm (Dorji et al. 2021), a slightly larger flake size was used for the pilot to provide a greater void volume and prevent choking from biomass accumulation during long-term operation using real domestic wastewater. However, increasing the flake sizes to 40 mm x 40 mm, the specific surface area of the biofilter media decreased to 347 $m^2/m^3$ from 1,425 $m^2/m^3$ (30 mm x 30 mm), 1,623 $m^2/m^3$ (20 mm x 20 mm) and 1,903 $m^2/m^3$ (10 mm x 10 mm) (Dorji et al. 2021).

The plastic bottle flakes were mixed with sharp stone gravel and subjected to abrasive action in a concrete mixer for about 30 minutes (HEICO, India). This resulted in rougher flake surfaces to help accelerate attached growth of biomass to the media. The properties of the ABF media are presented in **Table 1**.

**Table 1**: Properties of the ABF media used in this study.

| **Media properties** | **Values** |
|---|---|
| Media flake size | 40 mm x 40 mm |
| Thickness of plastic flakes | ~ 0.20 - 0.40 mm |
| Specific surface area of packed media | 347 $m^2/m^3$ |
| Packed media porosity | 92% |
| Packed media density | 78.5 $kg/m^3$ |

|  |  |
|---|---|
| Types of plastic bottles | PET and PP |

### 2.3 Acclimatisation and operation of the pilot anaerobic bioreactors

The seeding and inoculation of the bioreactors were conducted using anaerobic sludge obtained from anaerobic ponds of the Phuentsholing City waste stabilisation pond (WSP), and the start-up procedure was followed as described below (de Lemos Chernicharo 2007). The seed sludge in the bioreactors was left unfed for 24 hours to develop anaerobic conditions and adapt to the environment inside the bioreactors. The UASB reactor was then filled with blackwater and the ABF with greywater diverted from the households to half of the ABF reactor volume. After 48 hours of seeding and inoculation period, the reactors were filled with wastewater and operated as a batch system for another 48 hours (Behling et al. 1997) followed by a continuous flow-regime (Behling et al. 1997). After reaching constant hydraulic loading of the bioreactors, the pilot system was then operated under steady design HRT; 2 d for the UASB (~ 200 L/day) for 262 days and 0.37 d (~ 8.8 h) for the ABF (800 L/d) throughout a year.

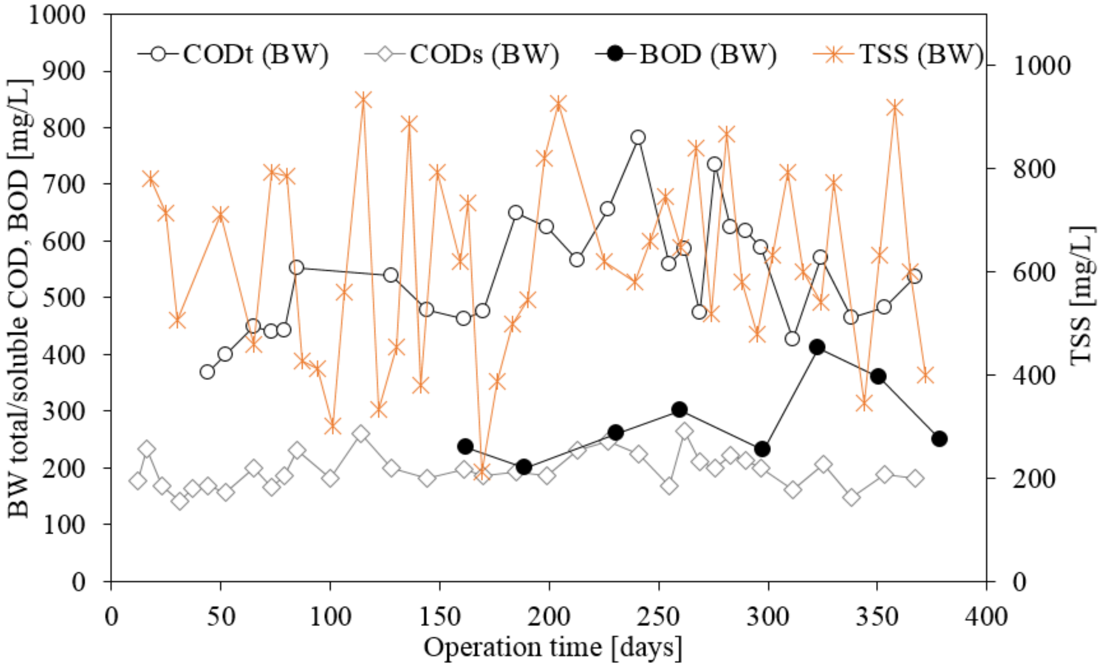
### 2.4 Wastewater analysis and performance monitoring

The performance of the pilot system was monitored rigorously, recording various parameters including pH, oxidation-potential (ORP), dissolved oxygen (DO) and temperature (all measured using Vernier Lab Quest, USA) and turbidity (HACH, USA). The total suspended solids (TSS) and the volatile suspended solids (VSS) were determined as per US standards (APHA 1998). Organics including total COD (CODt) and soluble COD (CODs) were measured using analytical test kits (HACH, USA) and DR3900 Spectrophotometer (HACH, USA). $BOD_5$ was measured using OxiTop®OC100 (Germany). *Escherichia coli* was measured as per the standard operating procedure at the Royal Centre for Disease Control – the National Water Reference Laboratory in Bhutan – to US standards (APHA 1998). Biogas samples were collected from the GLSS in the UASB and ABF using 10 L and 5 L Tedlar gas bags, respectively (Sigma Aldrich, Australia). The biogas and its composition were analysed using a Biogas Analyser 500 (GeoTech, UK). Influent and effluent grab samples were collected from the UASB and ABF fortnightly in the morning (9 AM) where the generation of wastewater was at its peak, to obtain uniform and representative samples. Due to sheer volume of the samples involved, samples were analysed in duplicates for BOD, COD, TSS and VSS only during the initial stages of the pilot operations while later only single measurements were carried out except when analytical errors are envisaged. For other parameters such as pH, DO and ORP, samples were measured in triplicates.

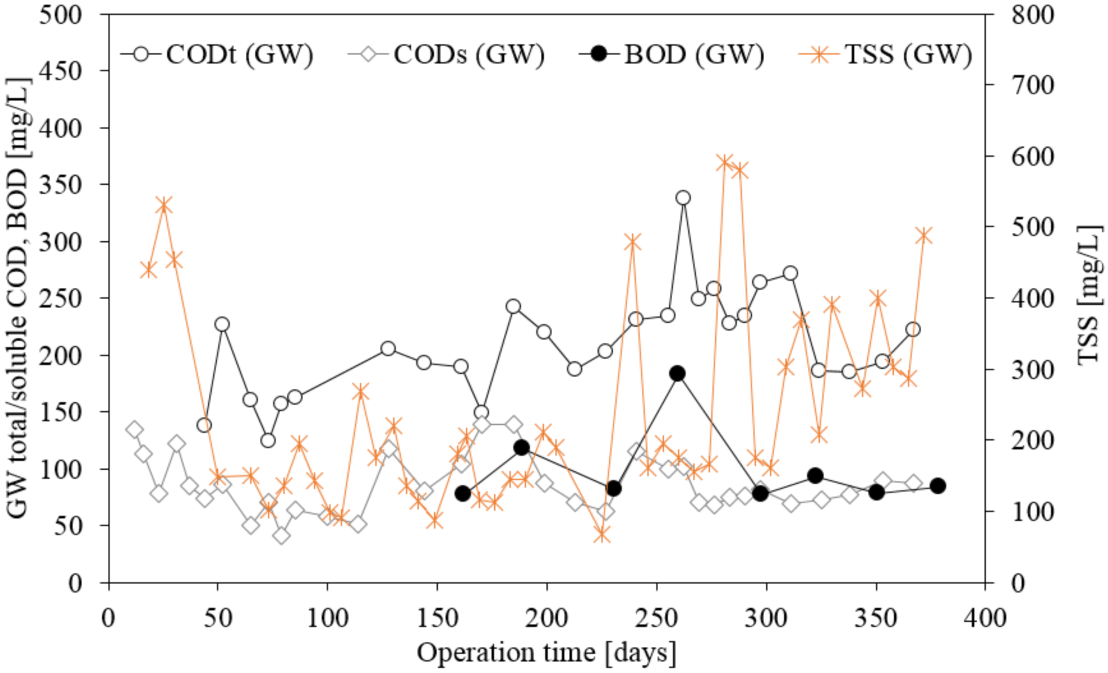
## 3. Results and Discussions

### 3.1 Wastewater characteristics

The characteristics of the wastewater (grab samples) from the residential building being treated by the pilot treatment plant were continuously monitored, and their features are presented in **Figure 2 (a)** for BW and **Figure 2 (b)** for GW. The CODt of the blackwater ranged between 367 - 782 mg/L (average of 539 mg/L) while the soluble COD (CODs) ranged between 140 - 265 mg/L (average of 183 mg/L), which can be classified as medium-strength domestic wastewater (Tchobanoglous 2014). The differences between the CODt and CODs indicate the presence of a significant concentration of suspended or other undissolved organics present in the BW. These average COD values are similar to the values reported in countries, including Turkey and the Netherlands, as presented in **Table S1** (Alptekin 2008) of the supplementary material. The BOD of the BW varied between 200 - 410 mg/L; however, due to limitations of the lab at CST, the BOD sampling and analysis was only possible in the later stage of the pilot. The average VSS/TSS ratio of 0.79 found is high compared with the sewage characteristics in other countries, probably due to the starch-rich diet (rice-based) of most Bhutanese. However, the low VSS/TSS compared to Egypt suggests more diluted wastewater in Bhutan than in arid Egypt.



(a)



(b)

**Figure 2:** Characteristics of the wastewater generated from the CST staff residential building and used as influent for the pilot treatment system. (a) Blackwater and (b) Greywater

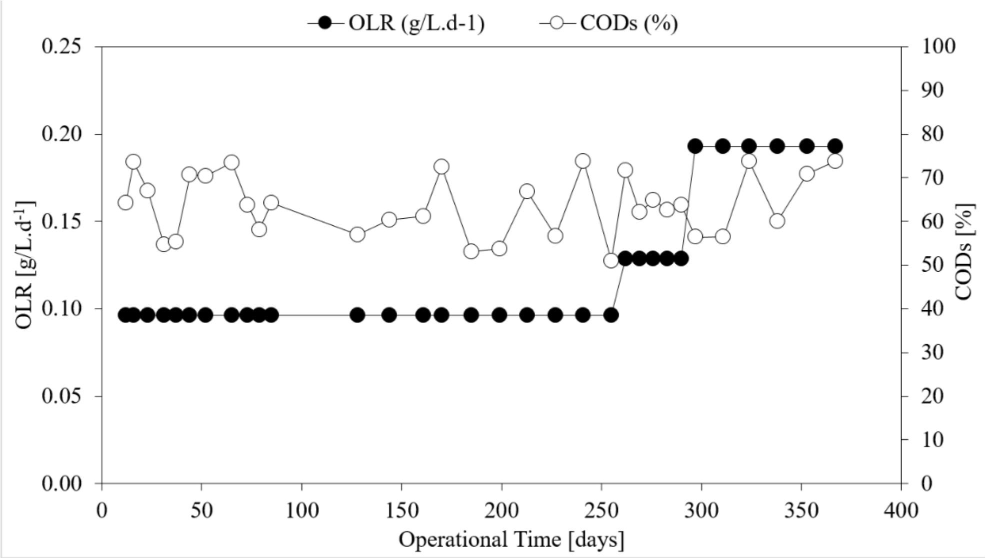
## 3.2 Start-up operations of the anaerobic bioreactors

Following start-up, the UASB reactor was operated continuously at 2-d HRT, and sludge acclimatisation was achieved after 262 days, indicated by consistent COD removal as shown in **Figure 3 (a**). The ABF was operated continuously for more than 300 days at 8.8 h HRT to achieve full acclimatisation as presented in **Figure 3 (b**). Anaerobic processes such as UASB and ABF usually take a long to achieve acclimatisation, which is one of the main challenges of anaerobic treatment.

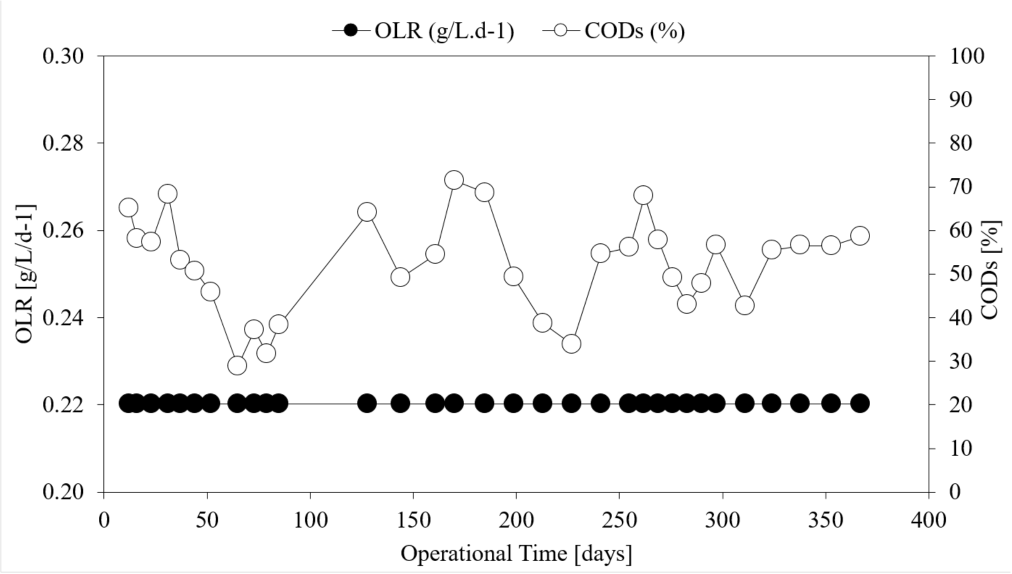
Anaerobic processes are sensitive to pH, and rising acidity as acidogenesis takes place. The influent alkalinity likely provided an adequate buffer for maintaining consistent pH in both the reactors (UASB influent pH 7.6 ± 0.4, effluent pH 7.2 ± 0.2; ABF influent pH 7.1 ± 0.2 and effluent pH: 6.8 ± 0.2; n=122) without the risk of souring even after a year of operation. This can be attributed to concurrent metabolic activities taking place during the anaerobic digestion process, where $CO_2$ generated as a by-product is partially dissolved in the wastewater to form bicarbonates that enhance the pH buffering capacity of the wastewater (Chiappero et al. 2019; Lettinga & Van Haandel 1994).

During the pilot operation period, the influent wastewater temperature ranged between 17 - 29°C, a sub-mesophilic temperature suitable for UASB operations (Ayaz et al. 2012). The ORP values of the wastewater inside both bioreactors were < -150 mV, indicating the presence of an anaerobic environment as presented in **Figure 3 (c**) and further supported by the methane production as shown in **Figure 4**. Wastewater with ORP below -

200 mV is an indication of high anaerobic conditions, but with limited potential for production of $CH_4$ (Srivastava 2020), since methanogenesis generally occurs within the ORP range of -230 mV to -210 mV (Santiago-Díaz & Salazar-Peláez 2017).



(a)



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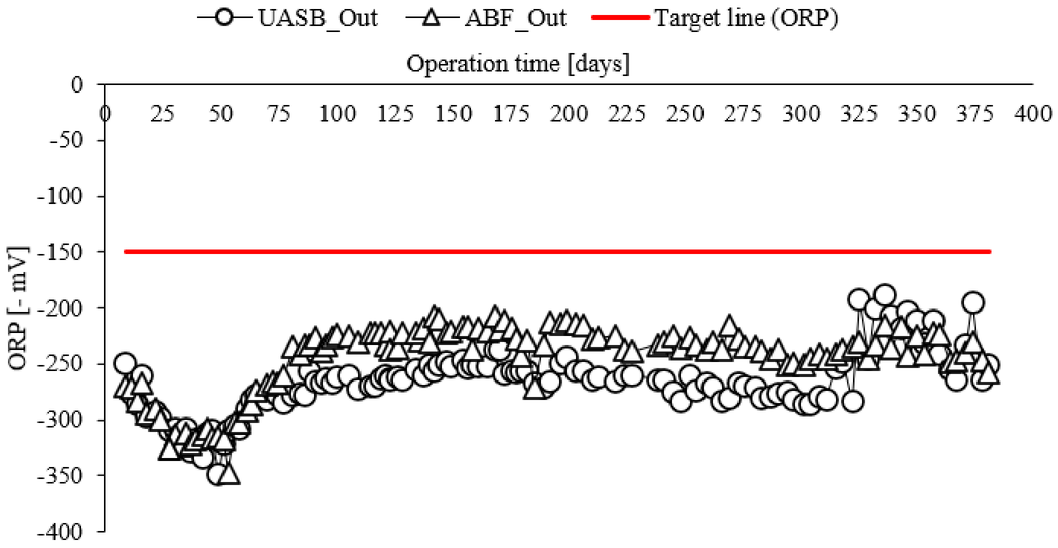


(c)

**Figure 3**: The OLR and the CODt removal of the (a) UASB reactor (b) ABF reactor throughout the pilot operation since the start-up stage and, (c) Oxidation-Reduction Potential (ORP) from the effluents of UASB and ABF.

### 3.3 Performance of UASB bioreactor for primary treatment of blackwater

#### 3.3.1 Organic (BOD/COD) removal and biogas production

The $BOD_5$/COD removal and the biogas production from the UASB reactor are presented in **Figure 4**. The removal efficiency of $BOD_5$ at 2 d HRT ranged between 73 - 75%, with a resulting effluent BOD of 54 - 75 mg/L, as shown in **Figure 4 (a)**. The effluent $BOD_5$ improved (46 - 55 mg/L) when the UASB was operated at HRT of 1 day, with a removal efficiency of 76 - 89%. This is likely due to the increased up-flow velocity causing improved mixing and distribution, optimising contact with biomass in the sludge granules (Mahmoud et al. 2003). This significant $BOD_5$ removal indicates the satisfactory methanogenic activity occurred within the sludge bed even under psychrophilic conditions suggesting that UASB treatment is suitable for conditions in Bhutan. For conventional primary clarification, the

$BOD_5$ removal typically ranges between 25 - 35% (O'Connor et al. 2015). $BOD_5$ removal of 73 - 89% achieved in this study with the UASB is better than the primary clarifier option. Based on the $BOD_5$ removal, 1-d HRT is adequate for the primary treatment of BW using a UASB, with the remaining BOD removed in the ABF to reach a target final effluent $BOD_5$ of 30 mg/L, the effluent discharge standard in Bhutan as shown in **Table 2**. These standards are based on the American Public Health Association (APHA) and the World Health Organization (WHO) (NEC 2020).

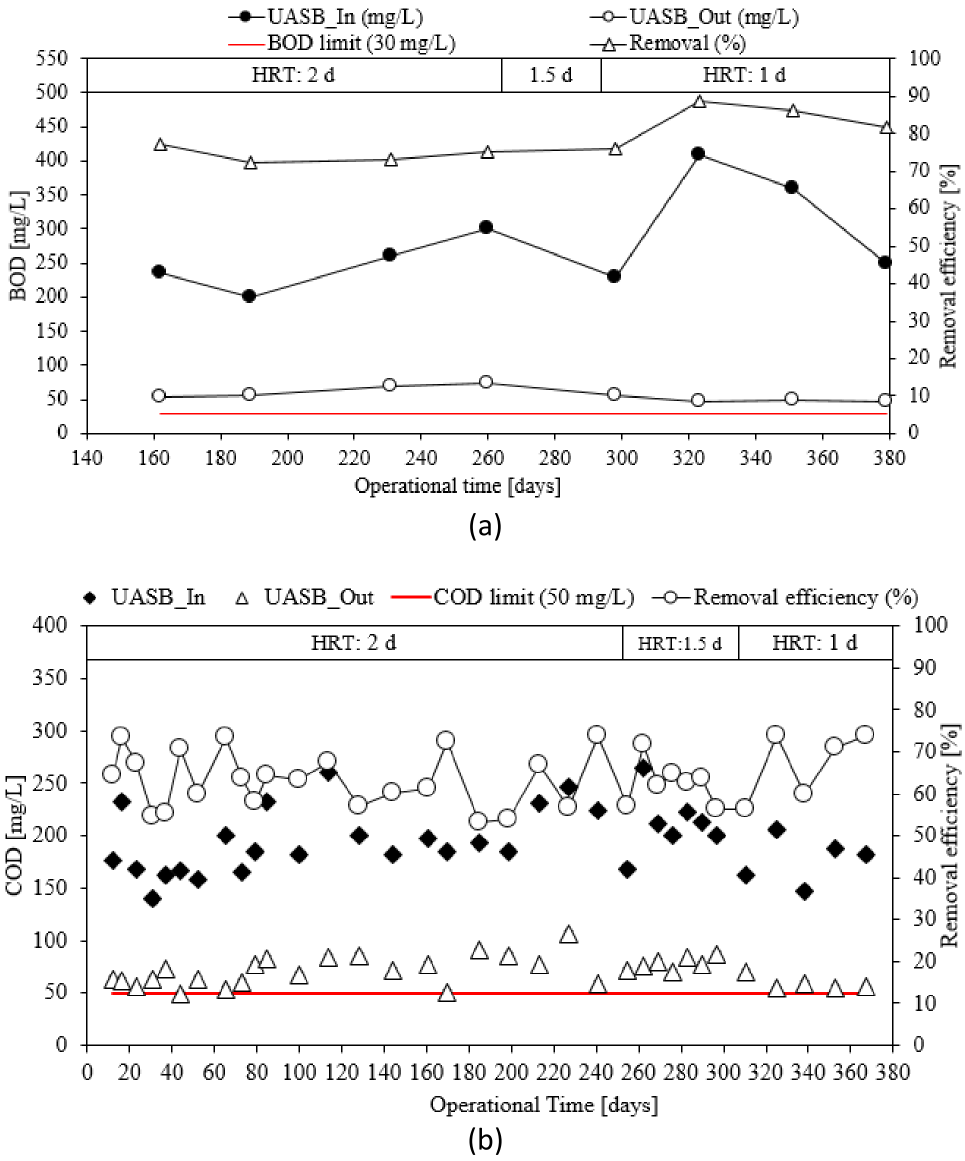
**Table 2**: Sewage treatment plant (STP) discharge standards (NEC 2020) .

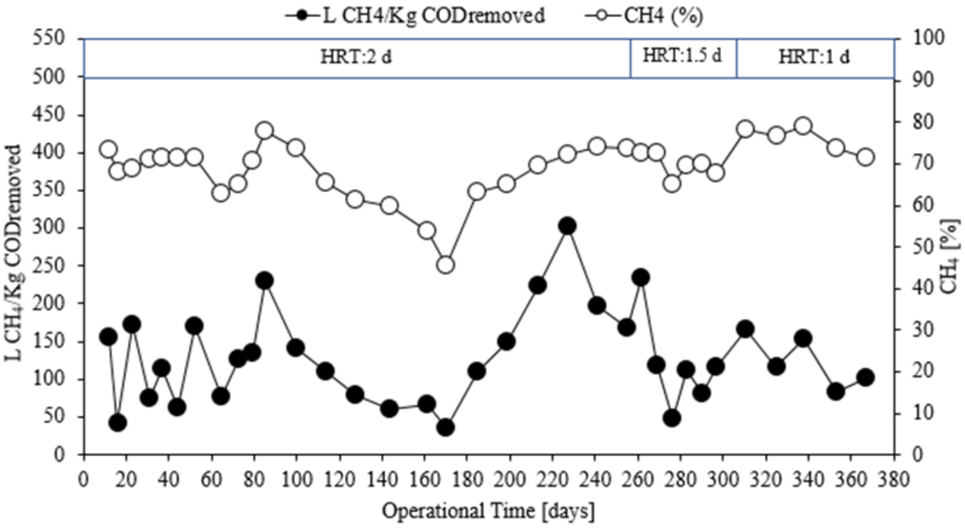
| Parameter | Unit | Standards |
|---|---|---|
| COD | mg/L | 125 |
| BOD |  | 30 |
| TSS |  | 100 |
| pH | pH scale | 6.5 - 9 |
| Faecal coliform | CFU/100 mL | 1000 |

At an HRT of 2 days, the UASB effluent COD varied between 49 - 107 mg/L (average COD of 71 mg/L) which translates to a COD removal of 53 and 74% (average of 63%) as presented in **Figure 4 (a)**. The COD removal did not vary significantly when the HRT was reduced to 1.5-d HRT. Similar to $BOD_5$ removal described earlier, decrease in HRT to 1 day improved the effluent COD to 56 mg/L, equivalent to COD removal of 70%, which almost meets the Bhutan effluent discharge limit for COD of 50 mg/L. Assuming a BOD/COD ratio of 0.6, and a minimum BOD discharge limit for sewage effluent in Bhutan of 30 mg/L. Similar to BOD removal, this improved COD removal at 1-d HRT is probably due to enhanced mixing and diffusion of organics within the granular sludge biomass (Mahmoud et al. 2003). This study, therefore, suggests that the optimum 1-d HRT produces effluent quality that almost meets the Bhutan effluent discharge standard in terms of BOD/COD. These results further demonstrate that UASB has the potential for the primary treatment of BW.

At the start of the UASB operation, methane generation varied widely ranging between 43 - 230 L $CH_4$/kg COD (or of COD removed) with an overall average of 128 L $CH_4$/kg COD during the entire pilot operation of as shown in **Figure 4 (b)**. This irregular methane generation could be due to random release of biogas that was already present either in dissolved form or in the form of micro-bubbles within the active anaerobic seed sludge collected from the anaerobic pond when subjected to up-flow turbulence (Feng et al. 2020). These methane generation values are similar to those reported in the literature (Ayaz et al. 2012). The methane generation and its proportion of the biogas increased from seeding day 65 - 85, probably as the seed sludge becomes more stable having adapted to the UASB environment. However, the methane generation then decreased between day 80 and 170, presumably responding to decreasing temperature with the start of winter, giving rise to psychrophilic conditions. Methanogens are sensitive to a lower temperature, and their biological activities can be significantly affected. From day 170 - 227, methane generation gradually increased with the start of the summer.

When the HRT of the UASB was reduced to 1.5 d, the methane generation decreased, and this is most likely due to increased OLR inducing shock loading of the UASB reactor as observed during the UASB treatment of cattle slaughterhouse wastewater (Musa et al. 2020). However, after day 276, methane generation and proportion recovered from the shock and operation became more stable. Although the biogas production was slightly lower at 1.5-d HRT compared to 2-d HRT, COD removal was consistent with a steady methane proportion, indicating the stability of the UASB granular sludge bed. Systems with higher rates of COD do not always also show increased biogas release (Manariotis & Grigoropoulos 2006). The proportion of methane in the biogas followed a similar trend as the methane generation, as presented in **Figure 4 (c)**. The methane proposition ranged between 45% (in cold winter months) to as high as 78% during the warmer months.





(c)

**Figure 4**: Performance of the pilot UASB reactor for the primary treatment of BW. (Organic removal in (a) BOD, (b) COD and (c) biogas production. Average reactor temperature (23.4±3.5°C) and ambient room temperature (23.7±3.7°C) with an average influent COD: 195 mg/L (as measured).

### 3.3.2 TSS removal

The influent and effluent TSS in the UASB averaged 612 ± 236 mg/L and 125 ± 55 mg/L respectively with a removal efficiency of about 80% during the stable period of pilot operations at 2-d HRT (see **Figure 5)**. During the initial stages of UASB operation (acclimatisation period) at 2-d HRT, the TSS removal efficiency decreased, which is presumed to be due to washout of seed sludge from the UASB reactor. However, after 50 days of operation, the effluent TSS concentration started to decrease. It stabilised within a range of 33 - 240 mg/L (averaging 125 ± 55 mg/L and 79.6% removal), which is close to Bhutan’s effluent discharge standard of 100 mg/L. When the UASB was operated at a reduced HRT of 1.5 d, the effluent TSS increased slightly to an average 148 ± 41 mg/L (78%). However, when the HRT from 1.5 d was decreased to 1 day, the TSS slightly spiked to an average of 232±79 mg/L (72% removal) before achieving a stable effluent TSS of 157±38 mg/L (73% removal). This slight spiking of the effluent TSS concentration is attributed to the increased up-flow velocity of the wastewater giving rise to turbulence might have disturbed the sludge bed resulting in temporary sludge washout. However, this stability under the HRT of 1 day resulted in a stable effluent TSS of 157 ± 38 mg/L (73% removal) which was higher than the average effluent TSS of 125 ± 55 mg/L (80% removal) at 2-d HRT. Similar TSS removal efficiency ranging between 45 - 84% have been reported for UASB in the other studies  (Heffernan, Van Lier & Van Der Lubbe 2011).

This anaerobic pilot operation was carried under ambient temperatures, and no correlation was observed between TSS removal and environmental temperatures. Similar observations were made by Hahn & Figueroa (2015)) during their 2-year long pilot treatment of wastewater using an anaerobic baffled reactor (ABR). The TSS removal (40 - 95%) is comparable to the highest reduction observed with the chemically added enhanced primary treatment ranging from 60 - 90% (Mau & Jeyanayagam 2008). However, the current treatment study does not require the addition of chemicals and neither wasting of solids from the reactor. The TSS removal exceeded the typical 50 - 65% removal for conventional primary clarification (Mau & Jeyanayagam 2008) indicating the advantage of using UASB as a primary treatment for domestic wastewater.

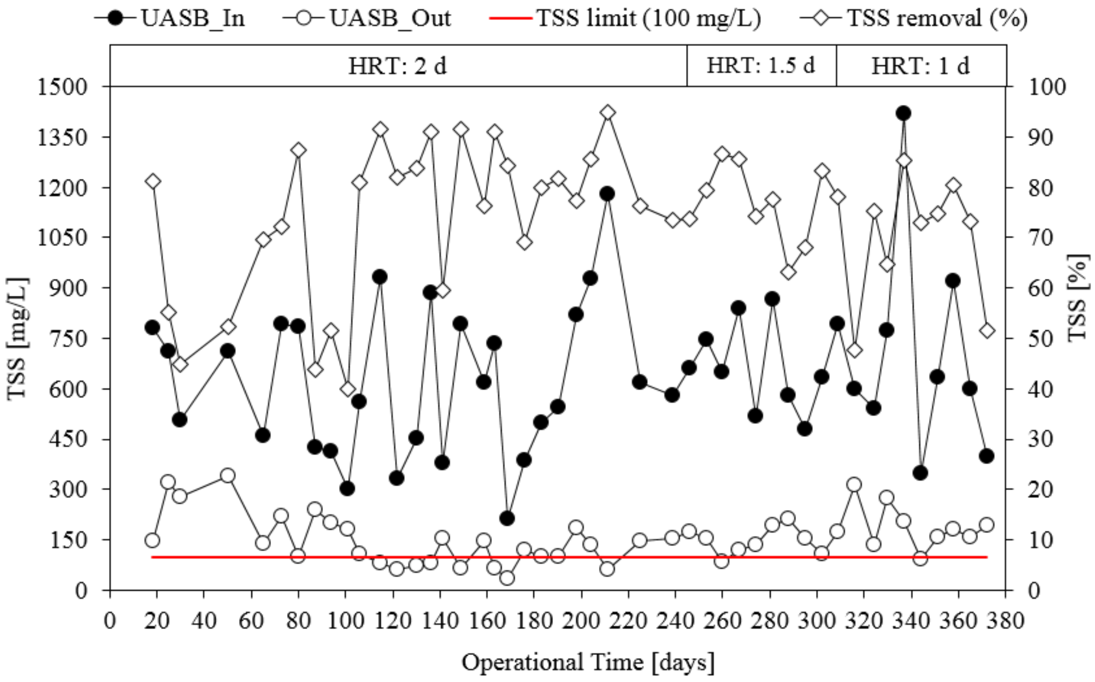


**Figure 5**: TSS removal in UASB under ambient conditions.

### 3.3.3 *Escherichia coli* removal

With an *Escherichia coli* discharge standard of 1000 cfu/100 mL, *Escherichia coli* is a critical water quality indicator because of the health hazard it poses. The log reduction of *Escherichia coli* from the UASB treatment of blackwater was 0.81 - 1.12 log values, equivalent to 84.6 - 92.4% removal efficiency as presented in **Figure 6**. The log removal did not vary significantly on the reduction of UASB HRT, with a relatively consistent average of 0.92 log units under 1-d HRT. This log reduction of *Escherichia coli* is lower than the log reduction of 1.90 units reported for a UASB reactor in Sweden for municipal wastewater treatment under HRT of less than 24 h (Samhan, Al-Sa‘ed & Mahmoud 2007).

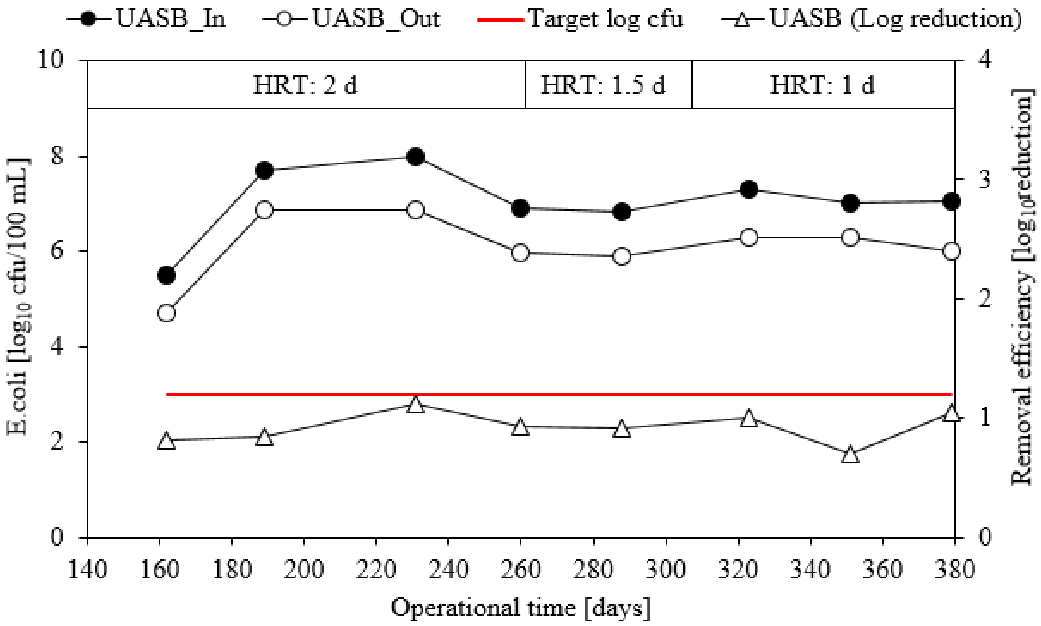


**Figure 6**: Performance of the pilot UASB reactor in the removal of *Escherichia coli*. The *Escherichia coli* data before day 161 are not available due to issue with the analytical equipment.

### 3.4 Performance of ABF for secondary treatment of mixed UASB effluents and greywater

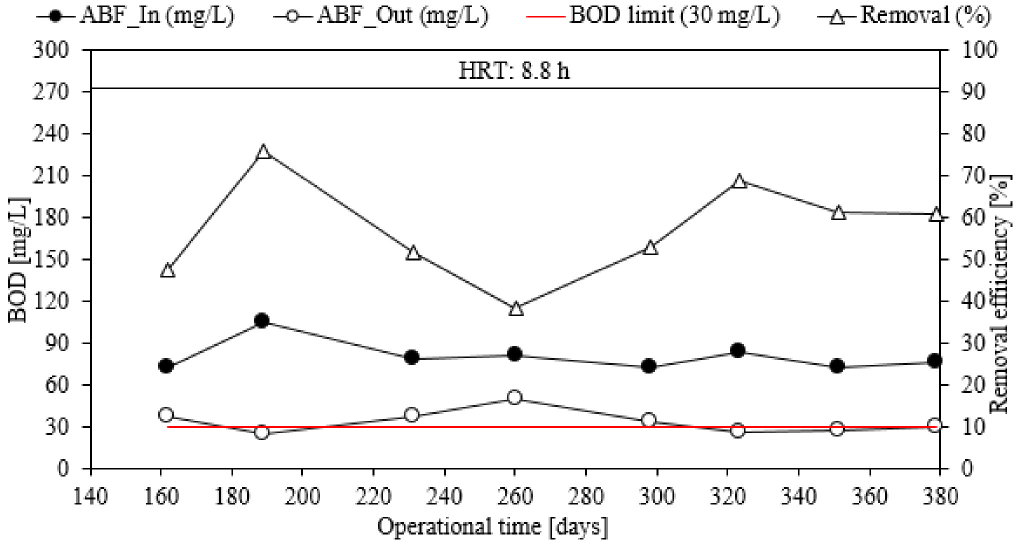
#### 3.4.1 Organics removal and biogas production

The long-term performance of the ABF for $BOD_5$ and COD removal and methane generation at a constant HRT of 8.8 h are presented in **Figure 7**. $BOD_5$ sample testing could only commence after 162 days of ABF operation. Although the effluent $BOD_5$ from the ABF was initially mostly above 30 mg/L; after day 300 after the initial effluent $BOD_5$ test from day 162, the effluent $BOD_5$ was consistently below 30 mg/L (average $BOD_5$ of 28 mg/L and 60 - 70% removal) as shown in **Fig 7(a)**, thereby meeting the effluent discharge standard for Bhutan. The $BOD_5$ removal rate of the ABF is slightly lower than the UASB reactor which is expected because the ABF influent consists of a mixture of UASB effluent ($BOD_5$: 46 - 75 mg/L) and greywater ($BOD_5$: 77 - 93 mg/L), having a resulting $BOD_5$ of 72 - 84 mg/L during the operation period. The $BOD_5$ removal of 60 - 70% was slightly lower than the 80% $BOD_5$

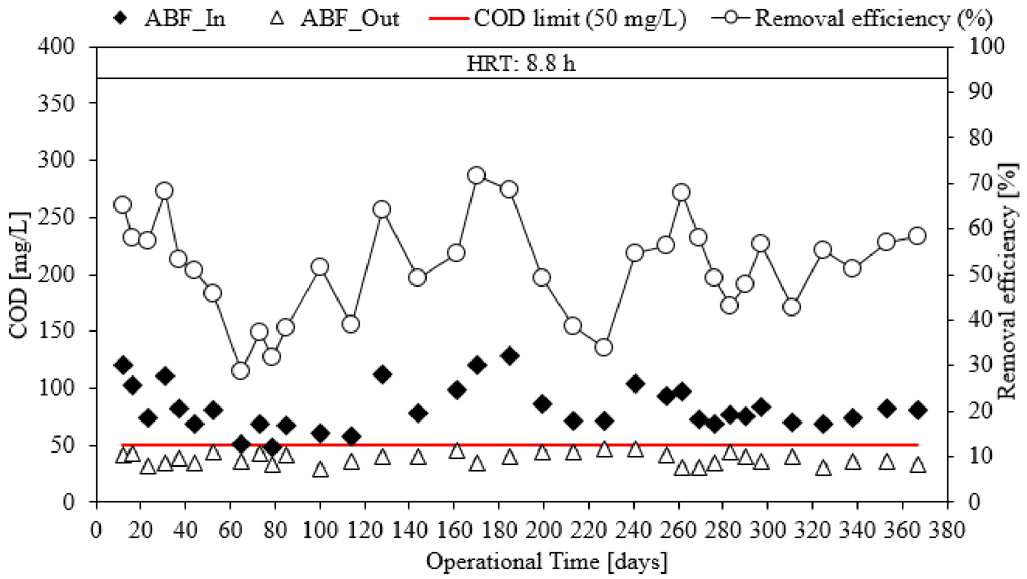
removal reported for an up-flow anaerobic filter comprising tezontle biofilter media treating municipal wastewater (Merino-Solís et al. 2015). This pilot study, therefore, suggests that shredded waste plastic bottles have the potential to be a suitable biofilter media for domestic wastewater treatment. The ABF was operated at a fixed HRT of 8.8 h based on our earlier lab-scale study; however, further process optimisation may enhance organic removal to achieve lower final effluent $BOD_5$.

**Figure 7 (b)** also shows that at a constant HRT of 8.8 h, the ABF produced an effluent COD ranging between 29 - 47 mg/L (29% and 72% removal efficiencies) and consistently 100% of the samples were below the target limit of 50 mg/L for Bhutan. These effluent COD (average of 38 ± 5 mg/L) and COD removal efficiencies (29 - 72%) were not significantly different from those observed during the lab-scale study (Dorji et al. 2021). The large variations in the removal efficiencies of 29 - 72% are attributed to the large fluctuations in the incoming domestic greywater COD (48 - 128 mg/L) (see **Figure 2 (b)**). These COD data and the BOD data presented earlier indicate the likely potential of the shredded waste plastic bottles as a promising low cost, locally available biofilter media for the treatment of both the mixture of primary effluent and the greywater. The COD removal performances of the biofilter can be attributed to several factors including the large surface area provided by thin plastic bottles for biological attached growth, the curved nature of the bottle shreds and the roughened texture of the plastic media that supported the development of the microbes. Compared to the surface area of biofilters such as coconut shells (100 $m^2/m^3$) (Tonon et al. 2015), shredded waster plastic bottles provided a large surface area of 347 $m^2/m^3$ and high porosity (92%) for the growth of biomass that enhanced biological degradation of organics.

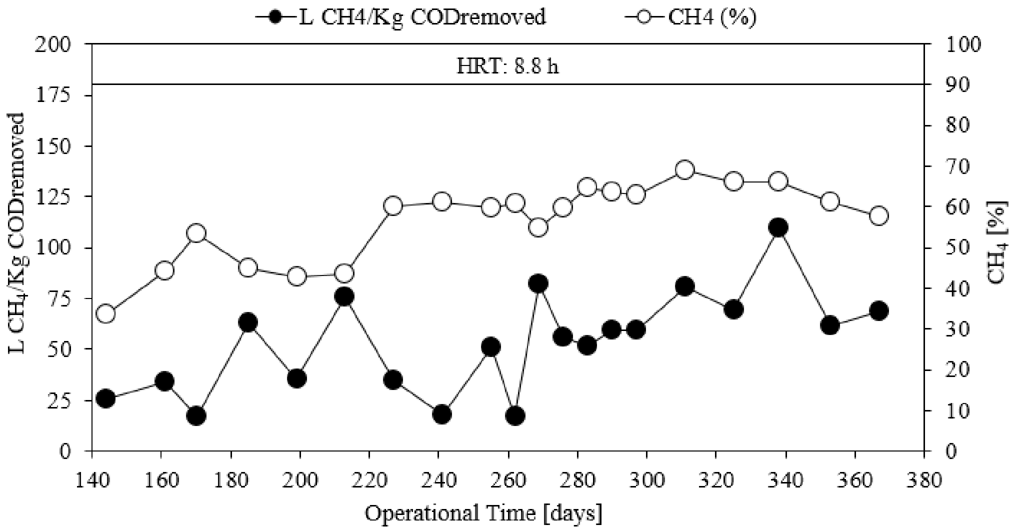
Due to some technical issues, biogas from the ABF reactor was only tested from day 144, and the results in **Figure 7 (c)** shows that methane production increased gradually as the ABF system slowly stabilised. Between day 140 - 170, even during the winter (17 - 24°C) steady methane production indicates methanogenic activity occurred even under psychrophilic conditions which is attributed to fully developed biomass within the waste plastic biofilter matrix aiding methanogenesis. Similar observations were also made in (Lettinga, Rebac & Zeeman 2001). After day 170, as spring began, the fluctuations in methane production (17 - 110 L CH4/kg COD) are attributed to the large fluctuations in the influent COD composition (48 - 129 mg/L) mainly due to the daily variations in the greywater composition. Consistent OLR is necessary for consistent methane generation from the bioreactors. The observed methane generation values are similar to those reported in the literature (Manariotis & Grigoropoulos 2006a).



(a)



(b)



(c)

**Figure 7**: Performance of the pilot ABF reactor for treatment of a mixture of UASB effluent and greywater (1:4 *v/v* mix ratio). Organic removal (a) in BOD, (b) COD and (c) Biogas production. ABF reactor temperature (23.37 ± 3.48°C) at ambient temperature (23.68 ± 3.65°C).

### 3.4.2 TSS removal

The TSS data in **Figure 8** shows that the influent TSS (mixed UASB effluent and greywater) ranged between 83 - 502 mg/L which is explained by the highly variable nature of the grey water coming from the residential buildings as the outflow of kitchen and bathroom wastewater are unpredictable. During the early stages of ABF treatment, following start-up operations, a significant spike in the influent TSS was observed and is attributed to washout of the seed sludge from the UASB reactor (as discussed earlier under **Section 3.3.2**) as shown in **Figure 5**. It is also likely that this seed sludge washout also contributed to the higher effluent TSS from the ABF during initial stages of operation. After day 40 of operations, the effluent TSS stabilised, but still varied significantly (33 - 127 mg/L) with an average effluent TSS of 80 ± 22 mg/L (average removal efficiency of 62%). Over 80% of the ABF effluent samples had TSS below 100 mg/L, which is the effluent discharge standard of Bhutan. This demonstrates the suitability of shredded waste plastic bottles as a possible biofilter media for removing TSS from domestic greywater. To achieve consistent TSS below 100 mg/L, further process optimisation can be carried out; adjusting HRT (probably increasing the ABF HRT), increasing the density of the biofilter media or providing a second ABF reactor.

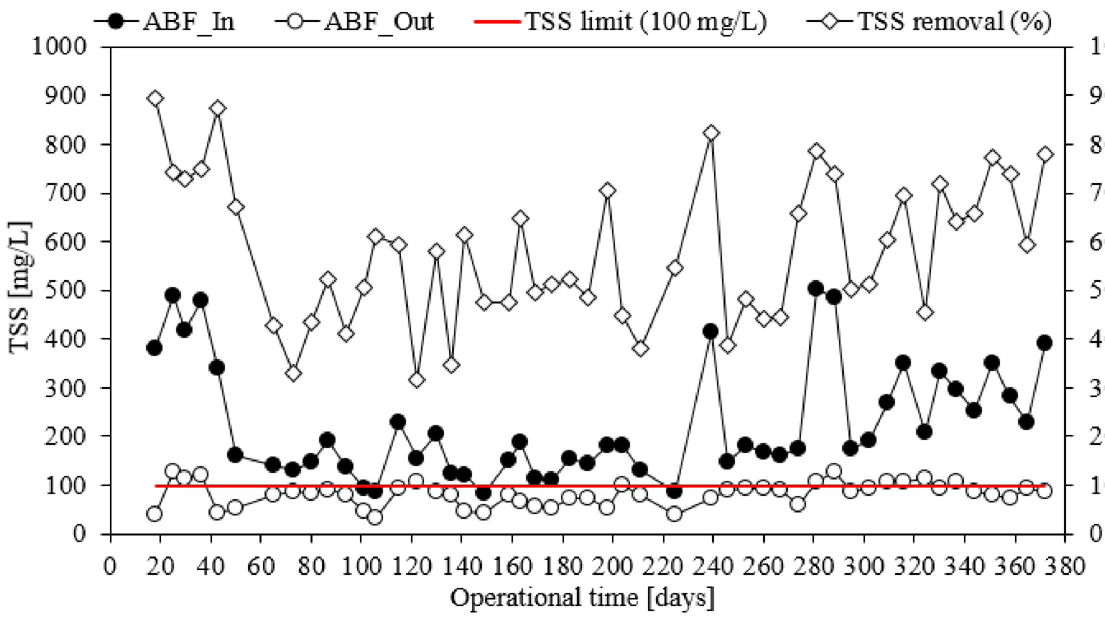


**Figure 8**: Performance of the ABF for the removal of TSS from the mixed UASB effluent and greywater.

### 3.4.3 *Escherichia coli*

The measured influent ABF and effluent *Escherichia coli* are presented in terms of their log units in **Figure 9**. The final average *Escherichia coli* reduction from ABF was 0.9 log units. This reduction in *Escherichia coli* are found to be in range between 0.78 - 1.02 log reduction units for other filter media such as biochar, woodchips, and gravel filters reported to range (Kaetzl et al. 2018). Biochar has been found to have better *Escherichia coli* removal because of higher pathogen adsorption rates on biochar particles due to its polarity. The final ABF effluent showed on average 5 log units of *Escherichia coli* (~ $10^5$ cfu/100 ml) which does not meet the allowable 3 log units (~ 1000 cfu/100 ml) effluent discharge limit of Bhutan.

This pilot of sequential UASB and ABF treatment using shredded waste plastic bottle media resulted in 0.4 - 1.5 log removal of *Escherichia coli*. A similar combined UASB and ABF however reported between 1 - 2 log removals using reticulated polyurethane foam as ABF media in terms of *Escherichia coli* removal (Alrajoula, Halalsheh & Fayyad 2009). It appears that the performance of the ABF reactor has a significant influence on the potential reduction of *Escherichia coli*. Therefore, through better process design and optimisation of the UASB and ABF combination, *Escherichia coli* removal would need to be further improved to meet Bhutan's standards.

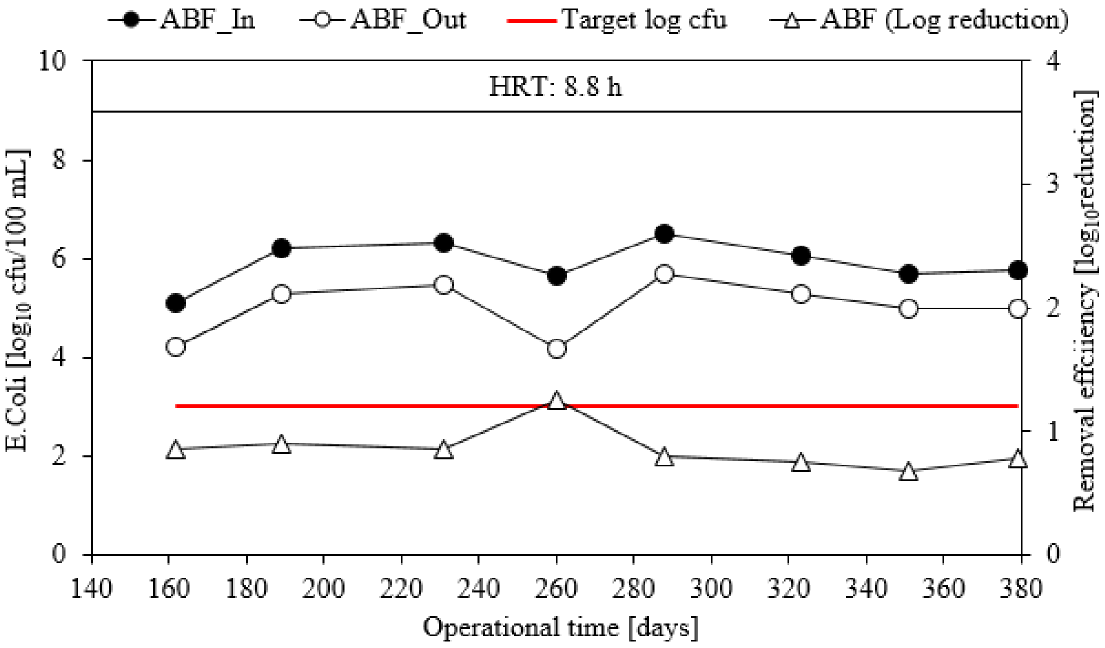


**Figure 9**: Performance of the ABF in the removal of *Escherichia coli*

### 3.5 Economic assessment

A brief economic assessment was carried out to compare the capital expenditure (CAPEX) and operating expenditure (OPEX) of this alternative on-site wastewater treatment system to the conventional on-site "septic tanks" currently predominant in Bhutan. The capital costs of a reinforced cement concrete (RCC) based "septic tank", and soak-pit were obtained from the Bhutan Schedule of Rates-2020 (MoWHS 2020). The unit costs of RCC work was then applied to estimate the capital cost of the UASB and ABF treatment system with 30% added price to account for additional construction complexities of the UASB and ABF reactor tanks. Further work, including plumbing, gas-liquid-solid-separator (GLSS) and the effluent weirs were estimated based on the BSR 2020 (MoWHS 2020). The plumbing from the residential buildings up to the “septic tank” or the UASB reactor is not included in the estimate as this is required for both systems. Additional information, including economic analysis worksheet, can be found in the supporting information (Refer to **Table S2** & **Table S3**).

The results in **Figure 10 (a)** show unless treating population equivalents of at least 50 people, the total monthly cost (CAPEX + OPEX) is significantly higher than for the current “septic tank” systems. For a 15 person system, the total unit cost of the new system is estimated at USD 0.84/PE/month, which is about 60% higher compared to USD 0.52/PE/month for a conventional system. The total cost difference reduces to USD 0.58/PE/month for a 25 user system which is only 38% higher compared to USD 0.42/PE/month for the conventional system. However, for larger system such as 50, 75 and 100 PE, the total unit cost for the new system is cheaper by 7 - 10% compared to conventional treatment. For a 100 user system, for example, the total cost of the new system is USD 0.27/PE/month compared to USD 0.29/PE/month for a conventional system. In terms of total cost per household, for 50 users system and above, the new system costs USD 1.57/HH/month compared to USD 1.74/HH/month for a conventional system and USD 2.04/HH/month for a DEWATS (refer **Table S4**). Since most modern buildings in Bhutan within the commercial and semi-commercial areas are expected to range within 50-100 PE, the cost implications on the new owner is insignificant. The government could provide limited subsidies to encourage adoption of new on-site treatment system for buildings with PE lower than 50.

**Figure 10 (b)** shows the contributions of CAPEX and OPEX to the total cost of the system for different numbers of users. OPEX is the major cost component of the new on-site wastewater treatment system (53 - 66%) compared to “septic tanks” where the CAPEX forms the major cost component (68 - 78%). The per capita OPEX cost component of the new system decreases at a larger scale.

If sufficient methane is produced from the two bioreactors to be used as energy, it could mitigate the monthly operating costs of the treatment system. Based on the measured average of 128 L $CH_4$/kg COD for UASB and 54 L $CH_4$/kg COD for ABF, it would require about 750 PE to produce enough methane to supply to one household (5 people) for their daily cooking usage in Bhutan, assuming a 14.2 kg LPG gas cylinder lasts about a month for each household (MoEA 2019). This indicates that methane capture and collection from this new wastewater treatment system cannot be claimed as a benefit for a single building. However, if the biogas from the on-site treatment system of all the buildings within the neighbourhood is collected, it may be able to generate enough biogas viable for supplies to several households and thereby helping prevent the release of the highly potent greenhouse gases from the treatment system.

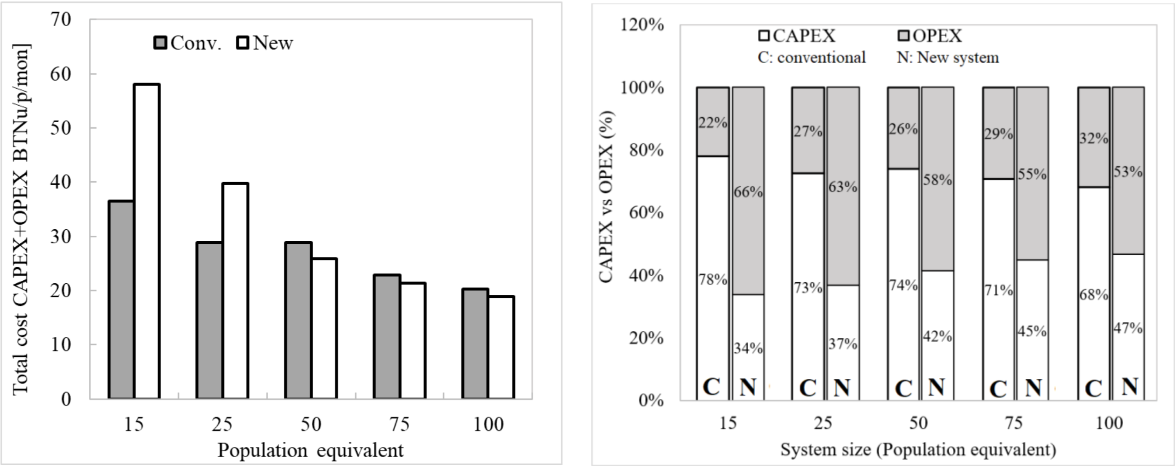


**Figure 10**: Comparative economic analysis of the new (N) improved on-site wastewater treatment system (UASB + ABF) and the conventional (C) on-site sanitation system ("septic tank" and soak pit). (a) Unit total cost (CAPEX + OPEX) and (b) Cost components of CAPEX and OPEX. Economic parameters: economic life 30 years & interest rate of 10%.

## 4. Conclusions

An on-site wastewater treatment system consisting of a combined UASB and ABF in sequence with a total 1,000 L/d capacity was piloted for treating domestic wastewater for about a year in Bhutan. The following conclusions are drawn from this study:

1. The pilot system produced a final treated effluent quality with an average $BOD_5$ of 28 mg/L, COD 38 mg/L, TSS 85 mg/L and 5 log units of *Escherichia coli*
2. The pilot effluent meets three out of four of the effluent discharge limits of Bhutan, and could not meet the *Escherichia coli* standard. However, further process optimisation may enable greater *Escherichia coli* removal and hence is an interest of future research.
3. An economic analysis indicates that, for a building with over 50 population equivalent, the cost (CAPEX and OPEX) of the piloted wastewater treatment system is 7 - 10% lower than conventional septic tanks.

This study, therefore, validates the earlier lab-scale study that a combined UASB and ABF (using shredded waste plastic bottles) can be effective in the treatment of domestic wastewater as an alternative to "septic tanks" that risk discharge of a poorly treated effluent to the environment. This new wastewater treatment system could contribute to protecting the environment from wastewater pollution, but also help reduce the financial burden on the local government from the investment in expensive sewerage infrastructure.

## Acknowledgements

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