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A combined up-flow anaerobic sludge blanket and biofilter as an improved alternative on-site sanitation in urban Bhutan: lab-scale to pilot studies

by Ugyen Dorji

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Under the supervision of Dr Sherub Phuntsho & Professor Hokyong Shon

University of Technology Sydney
Faculty of Engineering and Information Technology

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, ***Ugyen Dorji*** declare that this thesis, is submitted in fulfilment of the requirements for the award of ***Doctor of Philosophy***, in the ***School of Civil and Environmental Engineering/Faculty of Engineering and Information Technology*** at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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(**Ugyen Dorji**)

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LISTS OF ABBREVIATIONS

UASB	Up-flow anaerobic sludge blanket
ABF	Anaerobic Biofilter
HUASB	Hydrolytic Up-flow Anaerobic Sludge Bed
DEWATS	Decentralised Wastewater Treatment System
COD	Chemical Oxygen Demand
BOD	Biological Oxygen Demand
TSS	Total Suspended Solids
VSS	Volatile Suspended Solids
E. coli	Escherichia Coli
TKN	Total Kjeldahl Nitrogen
RGoB	Royal Government of Bhutan
UNSEPA	United States Environmental Protection Agency
WWTP	Wastewater Treatment Plant
NSBB	National Statistical Bureau of Bhutan
MoWHS	Ministry of Works and Human Settlements
WSP	Waste Stabilisation Pond
NEC	National Environment Commission
PET	Polyethylene Terephthalate
SRT	Solid Retention Time
MUASB	Modified Up-flow Anaerobic Sludge Blanket
NSSB	National Statistical Bureau of Bhutan
GLSS	Gas Liquid Solid Separator
ABR	Anaerobic Baffled Reactor
UAF	Up-flow Anaerobic Filter

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ABSTRACT

As of 2017, coverage of piped drinking water supply in Bhutan is about 98% and even higher in the urban areas. Still, Bhutan has been struggling to meet the demand for urban infrastructure following rapid and unplanned urban growth, including for domestic wastewater management. Public sewerage infrastructure and centralised wastewater treatment plants require capital for construction and operation. Therefore on-site wastewater treatment is expected to continue to play a significant role in the disposal of domestic wastewater in urban areas of Bhutan. Due to several challenges to the predominant "septic tank" situation, there is an increasing need for an alternative system for the safe disposal of combined black and grey wastewater in urban Bhutan. This Thesis aims to investigate a compact on-site domestic wastewater treatment system as an alternative to "septic tanks", some of which are used without an on-site soak-pit. The Thesis is composed of seven chapters, of which four chapters are technical studies.

The first study involved a survey in reviewing and understanding the current wastewater infrastructure and related challenges in urban Bhutan. This study observed that only about 23% of the classified towns in Bhutan are currently connected to public sewerage systems which represent the coverage of about 20% of Bhutan's total urban population, or 7.4% of Bhutan's entire population. Over 80% of Bhutan's urban population therefore depends on the on-site treatment of their domestic blackwater, with most greywater simply being discharged to surface water drains without treatment. However, over 40% of the properties with "septic tanks" lacked a soak-pit required for subsoil treatment of septic tank effluent, indicating unsafe disposal of potentially hazardous septic tank effluent posing significant risks to the public and the environment. Survey of urban plots suggests that the current practice of urban development has led to a situation where the regulation off-set/setback distances cannot be met to safely accommodate soak-pit within the plot with limited vacant space. This raised the need to explore alternative on-site treatment systems that does not require soak-pit but which could handle both black and grey water, to provide a safe solution for domestic wastewater disposal until networked public sewerage system is delivered or for areas where network sewerage is technically or financially not feasible.

The second study explores an up-flow anaerobic sludge blanket (UASB) and anaerobic biofilter (ABF) in series as an alternative on-site domestic wastewater treatment for modern urban settings in Bhutan. The UASB replaces the current septic tank for primary treatment of blackwater. In contrast, the ABF replaces the soak-pit (soil treatment) instead of further treatment of septic tank effluent combined with greywater. While septic tank and UASB can be comparable in terms of the footprint however, ABF can have much smaller footprint compared to large area required for the disposal of septic tank effluent in the soil using a soak-pit system. Hence UASB and ABF can be

much more compact solving the space constraints faced by the urban plots, unlike the extended space occupied by the septic tank and soak-pit system restricting the utility of limited urban space. The proposed alternative system used shredded waste plastic bottles as a novel biofilter media providing a large surface area for attached biological growth. The use of waste plastic bottles not only mitigate waste plastic problems in Bhutan but provide a locally available alternative biofilter media in place of commercial biofilter media which would have to be imported. A lab-scale UASB+ABF was operated for 188 days using synthetic wastewater (simulated black water and combined UASB effluent and greywater). At 2-day hydraulic retention time (HRT), the UASB achieved a chemical oxygen demand (COD) removal of 70 - 80%, biogas production of 200 - 230 L CH_4/ Kg COD removed with stable methane composition of above 70%. The best COD removal of 90 - 98% at 8 h HRT was achieved using the smallest (10 mm square) shredded plastic media size, attributed to large surface area per unit volume facilitating more significant attached growth of biomass compared to the larger media sizes (20 mm and 30 mm). The COD removal of the ABF decreased significantly at HRT of 6 h from the initial HRT of 5 days. The combined UASB and ABF at optimal HRT of 8.8 h achieved a final effluent with COD of less than 125 mg/L that meets the National Environment Commission or NEC's effluent discharge standard of Bhutan 2020. This lab-scale study showed that combined UASB and ABF treatment using shredded waste plastic bottle media has the potential for use as an alternative on-site sanitation wastewater treatment.

In the third study, the combined UASB and ABF treatment system was operated at pilot-scale in the field in Bhutan for one year with a capacity of 1000 L/day, equivalent to 2 households (10 population equivalent). The UASB received 200 L/day of blackwater while the ABF received 1000 litres of combined UASB effluent and greywater. Operated at 2-day HRT, the UASB achieved a COD removal of 43 - 74% while ABF with plastic media (40 mm square) achieved a COD removal of 29 - 71% at 8.8 h HRT. The combined UASB-ABF treatment achieved final effluent COD of less than 125 mg/L, BOD less than 30 mg/L and TSS less than 100 mg/L which meets Bhutan's NEC 2020 effluent discharge standards. The UASB and ABF reactors recorded a methane production of 0.80 - 26.09 L/d and 0.81 - 11.95 L/d with methane yield of 66.49 mL/g VSS removed and 45.96 mL/g VSS removed, respectively.

In the fourth study, three different locally available biofilter media were explored and tested for use in the ABF for treatment of a combined UASB effluent and the greywater and their performances compared to a commercial biofilter. The locally available biofilter media included shredded waste plastic bundles (3, 5 and 7 mm strip width), charred bamboo beads (cut fraction of 1/8 (~ 10 mm), 1/4 (~ 20 mm), 1/2 (~ 40 mm)), industrial slags (8, 10 and 12.5 mm sizes) and commercial media (10.5 mm). This lab-scale study was carried out initially using synthetic wastewater and then finally using real wastewater (obtained from the pilot UASB effluent mixed with domestic grey-water from the pilot site). These lab-scale experiments were operated under different HRTs of 12 h, 8 h and 6 h.

All three test media were able to achieve effluent COD concentrations that meet the equivalent national COD effluent standard, at all three different HRTs. The effluent turbidity of all the biofilters were above the NEC 2020 water standard of 5 NTU. The biofilter media sizes influenced COD removal rates, although HRT had the primary influence on COD removal. During the 150 days of operation, the smaller sized slag and bamboo medias achieved better removal under longer HRT of 20 h. While, the larger media sizes of slag and bamboo achieved better efficiency under the shorter HRT of 6 h. The smaller plastic strips of 3 mm with large surface area achieved better removal efficiency under the different HRTs. The smaller media sizes provide larger surface area for the attached growth and hence are expected to have better COD removal rates; however, it seems media porosity also significantly influences the hydrodynamics and mixing of the influent within the columns which further impacted the COD removal efficiency.

From the above studies, it can be concluded that UASB and ABF in series have the potential for use as an on-site treatment alternative to the current "septic tank" and soak-pit system which currently predominates in urban Bhutan, especially where soil treatment by soak-pit is not feasible due to limited space or impervious soils. Shredded waste plastic flakes, which are low-cost and readily available locally, may be an effective biofilter media for wastewater treatment. Their use as biofilter media could help reduce the mounting plastic waste problems in Bhutan. Improvement and optimisation of the process design and media design (shape and sizes) would help further improve the treatment capacity of this combined treatment system. However recently, the presence of micro-plastics in the aquatic environment has been acknowledged as one of the major environment concerns as this could pass through the food chain. The plastic biofilter flakes used in this pilot study were subjected to abrasion in order to increase the surface roughness of the generally highly smooth surfaces of the plastic bottles so as to enhance biofilm formation thereby possibly reducing the start-up time of the ABF. This abrasive force could increase the potential of producing micro-plastic during the preparation of biofilter media as well as its slow release during the long-term operations. Therefore, this is another area of research that needs to be considered in the future.

CHAPTER 1

INTRODUCTION

1.1 Introduction

This Chapter provides the overall synopsis of the approach taken by this Thesis. It presents the general background to global water and sanitation issues, global urban wastewater management approaches, institutional action and an overview of current urban wastewater management in Bhutan. It presents the motivation which instigated the research and the thesis problem.

1.1.1 Global urban wastewater management: issues, current approaches and challenges

Water scarcity is a dominating global issue, especially in developing countries. In many years to come, water shortages will persist. Water is an essential component of community survival and societal development, including animal species. Although 70% of the earth's surface is covered in water, only 2.5% is fresh water; of the total freshwater, 30% is contained in freshwater lakes, rivers and groundwater and the remaining 70% is stored as ice in polar caps, glaciers and permafrost soil (Gleick & Howe 1995). There is an increasing demand for freshwater due to the increase in the world's population and the contamination of available freshwater sources through human use and activities. The gap between demand and availability is geographically varied, affecting regions and countries differently. This mismatch in demand and availability gives rise to water shortages in some areas of the world with increasing frequency (Mekonnen & Hoekstra 2016). This has led to local disputes and regional conflicts more and more, particularly in the impoverished regions. In context to Bhutan in its entirety, it might not be construed as a significant issue in Bhutan. However, with the rapid urbanisation and changing lifestyles and industrial development, there is already increased demand for freshwater and a consequent increase in wastewater generation leading to inundation of on-site sanitation. Thus, there is a stake of public ill-health since there is an immense potential to affect the natural ecosystems and the national heritage sites due to continual discharges of wastewater from the on-site sanitation.

Under the millennium development goals (MDGs), the world's growing populations are entitled for access to improved sanitation and drinking water. Beyond the scope of MDGs, clean water and sanitation are basic requirements under sustainable development goals (SDGs) attributing to increasing world's population. The world's population, which stood at 6.97 billion in July 2011, has surpassed 7 billion and is estimated to reach 9.3 billion by 2050 (UN 2011). In particular, the population in the developing countries is projected to rise from 4.9 billion in 2011 to 6.3 billion in 2050 (UN 2011). Only about 68% of the global population (5 billion) had access to basic sanitation in 2015, while 4.5 billion people (61%) lacked regular access to safe sanitation services and a further 892 million people (12%) still practised open defecation (Desa 2016).

In developing countries, the private-sector plays an essential role supplying water and sanitation services to a substantial proportion of the population who do not have access to improved water supply or sanitation which is one of the MDGs (Davis 2005). In some countries, private firms are engaged by the government for operation and maintenance of water supply & sanitation infrastructure for specified periods (10 - 15 years) (Davis 2005). However, there have been cases of public opposition to private sector participation in water and sanitation services since it is perceived as a government's obligation to provide sanitation services and offer essential health to the public.

In developed countries, most on-site sanitation systems are constructed, operated and maintained by private building owners, and subject to strict legislation and environmental monitoring (USEPA 2002). Similarly, the majority of the on-site sanitation systems in developing countries are constructed, operated and serviced by private entities; but often lack institutional regulation of environmental discharges due to poor enforcement (von Sperling & de Lemos Chernicharo 2002). At the same time, there is often a lack of institutional interest to explore alternatives to current on-site sanitation treatment due to a lack of strategy and financial capital.

The generation of wastewater has increased in many regions around the globe though there is limited data collection, updating or disaggregation of data. Increase in wastewater is attributed to rapidly growing population, urbanisation, improved living conditions and economic development. In contrast, the disposal of wastewater is a growing challenge in urban areas of developing countries (Sato et al. 2013). Only about 10% of the wastewater generated is estimated to be treated in low-income countries (Malik et al. 2015). More than half of the cities in Latin America, Africa, the Middle East and Asia treat less than 50% of the wastewater collected, while in 56% of the cities the treatment plants are partly functional (Raschid-Sally & Jayakody 2013). With the advancement of MDGs over the years, the status of WWTPs operations are presumed to be better in 2020 with the project development of wastewater treatment likely above 50% from that in 2013 across the cities in the regions.

As the majority of the world's population live in developing countries, one of the most crucial challenges in the 21st century is to mitigate wastewater volumes through effective treatment to facilitate public well-being and public health. While more than one-third of the world's population lives in water-stressed countries where water demand exceeds the supply, mainly in developing countries, improper disposal of wastewater further aggravates available water and food security (Corcoran 2010).

1.1.2 Global wastewater treatment situation

1.1.2.1 Sanitation and on-site treatment

The available data suggests that high-income countries, on average, treat 70% of the wastewater generated and whereas only 8% of the wastewater generated is treated in low-income countries (Sato et al. 2013). In Asia, only about 32% of the wastewater generated is treated for safe discharge, primarily due to the lack of treatment facilities in many countries (Sato et al. 2013). The main actual limitation in Asia is the lack of financial resources, followed by the lack of well-defined policies and also shortages of qualified personnel deployed in the wastewater management sectors (UN 2000).

More than 90% of the wastewater generated is left untreated in low-income developing countries (Sato et al. 2013). Wastewater treatment in developing countries remains limited due to lack of investment and by not budgeting the continual increase in population forecast and the associated rise in wastewater production. Thus, increased wastewater volumes inundate the existing wastewater treatment plants resulting in ineffective treatment. At the same time, faecal matters and solid wastes often do not even reach treatment facilities but are disposed to surface water drains, ditches, and streams due to inefficient on-site treatment system. Such disposal leads to pollution of surface water-bodies contaminating irrigation and drinking water resources in the unsewered areas (Qadir et al. 2010).

Concerning unsewered areas, many countries experience problems with the performance of the "septic tanks". Treatment requires long hydraulic retention time (HRT), but due to conventional design or construction, high horizontal flows lead to unsafe effluents (Mgana 2003). Despite their wide use for the small-scale and decentralised treatment of domestic raw sewage in a septic tank in Brazil; effluent quality is often low, with COD removal ranging between only 30 - 50% (Van Haandel et al. 2006). Also, methane from septic tanks supplement to the greenhouse gas pollution and smell from the putrefaction in septic tanks add up to the indoor air pollution. Alternative on-site treatments have remained unexplored due to lack of private in-house capacity and meagre monitoring of existing on-site sanitation. Further, alternatives to the on-site treatment options are not pursued due to lack of initiatives and divergence of interests from public and private entities.

However, most of on-site sewage disposal systems (OSDS) provide an only partial treatment which is often considered a primary stage in wastewater management (Babcock et al. 2014; Oladoja 2017). This limitation of on-site treatment such as septic effluents demands effective wastewater management like further secondary treatment or treatment at WWTPs (Munda 1997). On the other hand, the potential for water savings like localised greywater discharge is high in the urban areas if each building can discharge its greywater locally. However, due to space limitations, the treatment technologies opted are assigned to have a small footprint (Friedler & Hadari 2006).

Most of the highly polluted effluents from "septic tanks" are discharged into sub-surface areas or infiltrated into the ground. Correspondingly, "septic tank" effluent is the most frequently reported source of groundwater contamination (Stevik et al. 2004). Even though septages may be transported off-site in cesspool tankers for further treatment at the central treatment plants; however, the wastewater is often not treated to the required discharge standard (Cakir 2004).

Therefore untreated or partially treated effluent is a source of excessive nutrients in downstream rivers, leading to eutrophication, as well as groundwater contamination by pathogens (bacteria and virus) and other persistent organic pollutants (POPs) such as pharmaceuticals and personal care products (PCPs) (Naidoo & Olaniran 2014).

1.1.2.2 Influent wastewater composition

Household wastewater includes only blackwater (faeces or excreta and urine) and greywater (bathroom, laundry, and the kitchen sink). Sources of domestic sewage are from private residential buildings (Tchobanoglous, Burton & Stensel 2003). Municipal wastewater mainly consists of domestic sewage but may also contain stormwater and industrial wastewater which might have infiltrated and got collected in the same public sewers (Zartman 2011). Usually, the inclusion of surface and greywater is considered detrimental to treatment, massively increasing plant capacity, where greywater accounts for about 70% of domestic wastewater (Friedler & Hadari 2006).

Greywater is often disposed into existing stormwater drains and open spaces without treatment since provisions are not kept for treatment (Katukiza et al. 2014). Notably, despite greywater being the largest wastewater pollutant, carrying pathogens, nutrients and micro-pollutants, the management of greywater in urban settlements is not given priority (Katukiza et al.

2012). It appears the treatment of greywater is often overlooked, and unsafe discharge of greywater is not perceived as a problem even (Seabloom & Carlson 1986).

However before the treatment, greywater accounts for 40% of the COD; therefore, the separation of greywater from the domestic sewage could lead to unfavourable C/N ratios during denitrification at the WWTPs (Morandi & Steinmetz 2019). Furthermore, separation of greywater from the domestic wastewater could lead to the long-term water stagnation in sewers due to the significant reduction of water during the dry weather flow. Especially, where there are low blackwater flows, sewers might get clogged. Therefore, instead of separating greywater, integrated treatment of combined blackwater effluents and greywater may aid synergistic treatment effects such as removal of organics and nutrient recovery both on-site and subsequently at the treatment plant, as well as generating useful biogas through the anaerobic treatment technologies.

1.1.2.3 Treatment technologies

In terms of environmental effects, technical capability, and financial capital, developed and developing countries have different priorities when it comes to selecting wastewater treatment technologies. Developed countries select treatment systems considering factors such as efficiency, reliability, sludge disposal and land requirements (von Sperling 1996). It appears centralised treatment technologies are efficient in managing urban domestic wastewater in developed countries such as the use of constructed wetlands (CW) due to the considerable potential of nutrients removal (Kivaisi 2001). Since constructed wetlands occupy a good amount of space, it seems space is not an issue in the majority of the developed countries for the treatment systems except with the few exceptions.

While selecting treatment systems in the developing countries, critical factors include construction and operation costs, sustainability and simplicity of operation and management (von Sperling 1996). The most widely used treatment systems in the tropical developing countries were waste stabilisation ponds (WSPs) due to the low cost of installation and maintenance, and optimum climatic conditions for WSPs (Kivaisi 2001). The performance of WSPs is satisfactory in many cases; however, WSPs require larger physical footprints than pond systems (1.2 - 5.0 m^2/person/d), constructed wetlands (3.0 - 5.0 m^2/person/d) (Von Sperling & de Lemos Chernicharo 2005) or anaerobic biofilters (0.08 - 0.25 m^2/person/d) (Kaetzl 2019). Due to unplanned growth and strategy, space is limited in the urban areas of many developing countries.

In addition to the larger footprint of WSPs, the managerial and technical capacity to address operational problems is often lacking in developing countries. Also, the failure of many treatment systems due to public opposition to wastewater treatment plants near community settlements make it difficult to operate likely due to health and smell issues (Massoud, Tarhini & Nasr 2009). Due to management and technical failures lead to discharging of untreated wastewater directly into the water-bodies result in environmental pollution (Senzia 2003; Shrestha 2001). This is often the case in developing countries.

In some countries, to meet stringent effluent targets, technically advanced and expensive treatment are used together with biological treatment (Renou et al. 2008). On the other hand, in difficult economic situations, use of local filter media can facilitate on-site wastewater treatment for developing countries with low transport connectivity to external markets and materials (Abbassi et al. 2018), such as in context to Bhutan.

Increased environmental legislation in developed countries provided the stimulus for the development of anaerobic wastewater treatment systems due to economic and environmental benefits over traditional aerobic techniques (Zakkour et al. 2001). Aerobic treatment, such as activated sludge or trickling filters showed high costs (USD 50 per person equivalent/year), unlike aerobic treatment, anaerobic treatment costs are half (Vandevivere 1999) without significant increase on reactors costs (Bressani-Ribeiro, Chamhum-Silva & Chernicharo 2019). Further, anaerobic treatment systems can be applied at any scale as an added benefit such as reduced sludge without external aeration costs (van Lier 2002). Options for low-cost system treatment are also associated with environmental protection in developing countries (Foresti 2001) facilitating the application of anaerobic technology (Foresti 2002).

When considering combined black and greywater treatment, greywater dilutes the wastewater, which makes it unsuitable for high-rate treatment system such as up-flow anaerobic sludge blankets (UASBs) in suspended sludge-bed systems. However, the treatment of greywater requires both physical and biological processes for the removal of particles, dissolved organic matter and pathogens. These physical and biological removal processes can be addressed by anaerobic biofilter (ABF) treatment using filter matrices and up-flow hydraulic regimes (Elmitwalli et al. 2007), which are missing in conventional "septic tanks". However, integrated treatment for combined blackwater and greywater from municipal sources has not significantly been researched (Morandi & Steinmetz 2019). In particular, the combined treatment of blackwater effluents from UASB and greywater are limited.

Thus, a combination of UASB and ABF seems to be suitable for the anaerobic treatment of domestic wastewater in developing countries (Alptekin 2008). The two-stage anaerobic sewage treatment of UASB+ABF in series seems to offer a suitable option for sewage treatment (Ghangrekar & Kahalekar 2003). The treatment of domestic wastewater can be economical if a large volume of wastewater can be treated in systems with relatively short HRT (Mgana 2003), which is feasible with ABF systems using local biofilters. An investigation is required to understand the potential of UASB+ABF systems on the functionality of the local biofilters in decentralised management contexts. Primary anaerobic treatment of wastewater combined with anaerobic secondary treatment significantly reduces biosolids and increase methane production from the effluent wastewater (Hahn & Figueroa 2015). Since biosolids from anaerobic treatment are digested, the sludges can be used for gardening after proper treatment with lime, while methane can be tapped and stored for domestic utilities. This significant reduction in the biosolids was found where UASB reactors constitute up to 70% of full-scale anaerobic sewage treatment installations around the world for the treatment of domestic wastewater (Bodkhe 2009). Thus, decentralised management of blackwater using anaerobic treatment technologies such as UASBs and ABFs has demonstrated localised benefits to end-users while mitigating environmental pollution (Gallagher & Sharvelle 2010).

1.1.2.4 Anaerobic treatment plants and biofilters

Most low-cost treatment technology, such as natural treatment systems, require extensive land, due to which such treatments cannot be applied in the areas with limited space (Brissaud 2007), particularly in the hilly landscape. However, ABFs have a high treatment capacity, with increased retention of biomass while requiring less site area and smaller reactors along with biogas production (Latif et al. 2011). This is due to the relatively high removal of substrates under lower HRT, less sensitivity to highly fluctuating influents while still achieving low suspended solids (SS) concentrations in the ABF with matrices of biofilter media (Stazi & Tomei 2018). Today, the ABF is still widely used in the treatment of sewage and is considered to be the precursor of the new modern high-speed systems developed in subsequent decades (Van Haandel et al. 2006). Due to these benefits, the necessity for separation and recycling of solids is eliminated, which is beneficial in context to the developing countries.

Other added benefits include the relatively quick recovery of ABF performance after a period of interruption due to media matrices. These features contribute to lowering construction, operation and maintenance costs of ABFs compared to other systems (Manariotis &

Grigoropoulos 2003). Mainly locally available materials such as rocks or plastics are generally used as filter materials for ABFs.

Around the world, granulated activated carbon (GAC) has become the most commonly accepted biofilter material for the growth of microbial biofilm in wastewater treatment plants (Asri et al. 2018). However, GAC production costs are high, and it is difficult to regenerate a biofilm, which limits the use of GAC as a biofilter material in context to a developing country. Therefore, for the adoption of ABFs in developing countries, high transportation or manufacturing costs can be a barrier to the use of imported materials (Frankin 2001). Also, the cost of filter materials can be equivalent to the construction costs of the reactor itself (Van Haandel et al. 2006). Thus, studies continue to search for low-cost alternative biofilter materials. Several studies have evaluated the application of different low-cost filling materials for ABF (Camargo & Nour 2001; Kaetzl 2019).

In the current field of sanitation, the major topics of research are: (a) drinking water; (b) sustainability; (c) biofilm; (d) epidemiology; and (e) WaSH (i.e. Water, Sanitation and Hygiene) (Huang & Zhou 2020). In particular, biofilm filter treatment approaches have the advantage of being ecologically low-impact solutions, requiring little or no chemical additives or electrical energy compared to other conventional systems (Jenssen 1996). Current research hotspots and several frontiers of sanitation research are also mainly focused on the sustainable growth of sanitation systems adapting to climate change (Huang & Zhou 2020). This includes the use of municipal plastic wastes generated for the on-site sanitation treatment systems.

The use of plastic wastes as the biofilter medium benefits the removal of pollutants from the municipal settlements and reduce localised pollutions loads by meeting the discharge standards of the wastewater outflow from the households. Thus, the suitability of UASB and ABF reactor can be evaluated not only in terms of operational conditions but also in terms of anaerobic performance in terms of organics and nutrients removal under varying organic loading rates. The improved treatment performance of the combined treatment system is attributed to the use and effect of biofilters since UASB+ABF system compliment as the combined on-site treatment system.

Such a UASB+ABF proposed combined system could realise financial and economic benefits in terms affordability through the economic assessment of new treatment plants compared to the existing ones. If implemented, septic tank effluent discharges from septic tanks should be significantly avoided due to conventional design. Besides, benefits such as reduction of indoor air pollution, improvement in public health due to an improved sanitation and greenhouse gas production were accrued due to the use of UASB as single house on-site sanitation (Lohani, Chhetri & Khanal 2015).

1.1.3 The institutional situation for wastewater treatment and water quality protection in Bhutan

The Ministry of Works and Human Settlement (MoWHS) and City corporations (municipalities/thromdes) are the leading agencies responsible for waste prevention and management in Bhutan. At the sub-national level, Dzongkhag Tshogdu and Gewog Tshogde supported by the technical team from respective municipalities are responsible for waste management, including domestic sewage with guidance from the Ministry of Health (MoH), while National Environment Commission (NEC) is the monitoring and compliance unit.

Although there is a national discharge standard for municipal centralised WWTPs, in particular, Bhutan lacks specific effluent discharge standards from private on-site sanitation at the individual household level. In the absence of effluent standards for the on-site sanitation, the discharge standards from sewage treatment plants (STP) are stipulated as given in **Table 1.1** below:

Table 1.1: Sewage treatment plant (STP) discharge standards (NEC 2020).

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

These standards are based on the American Public Health Association (APHA) and the World Health Organisation (WHO) (NEC 2020). In urban areas, these standards are suitable. Faecal coliform indicators are known to be regularly breached and lack monitoring and regulation arrangement capacity. Due to lack of legislation, enforcement and penalties are not levied. Complying with these discharges standards would reduce the risk of public health, although it cannot be eliminated. Given the importance of on-site treatment systems, it is in the interest of house owners to install an improved on-site treatment system supported by legislation. Although NEC will not be able to test effluents from all of these private UASBs and ABFs, it should be outsourced to private laboratory to take up the tasks at nominal rates.

Networked sewerage systems are considered the ideal solution for urban sanitation, with on-site systems, including “septic tanks”, as an interim solution to be phased out where possible. The 40.5% of the total buildings in the 33 classified towns use septic tanks without soak-pit considering the provision of future sewer network systems (Dorji et al. 2019) However networked sewer systems and centralised wastewater treatment plants are not appropriate in specific contexts and are yet to fully service any urban settlements in Bhutan (Carrard & Wangmo 2012). Other alternatives, such as more technological, more cost-effective and those within the technical and managerial capacity of the local authorities in terms of human resources and financing, are currently not considered in the absence of any consideration of the consequences of septic tank wastewater discharges. By allowing “septic tanks” to continue until networked systems are constructed, there is a risk that weak regulation and enforcement of “septic tank” design and operation leads to groundwater contamination and health risks.

The recent development of a revised draft National Hygienic and Sanitation Policy (2019) emphasises that safe sanitation facilities be put in the public places under the of MDGs (RGoB 2017). To achieve the Bhutanese environmental quality of minimal eutrophication and good quality groundwater, the government’s revised policy aims to include measures to be implemented in the locations with inadequate sanitation, including in urban areas. To improve the quality of on-site effluent, all conventional “septic tanks” could be replaced or retrofitted with other treatment technologies, e.g., anaerobic filters, to be identified by the technical institution and approved by the national government and implemented by the wastewater sectors and stakeholders. These retrofitted treatment systems will need to satisfy the established effluent quality standards and reap economic benefits without an increase in operation and maintenance costs (Hamisi 2019). To achieve this sustainability goal, use of locally available filter media may provide services through the integrated anaerobic treatment of domestic wastewater.

The current government budget does not enable sewerage to be provided to all buildings in the urban areas. Thus, it is necessary to promote improved on-site alternative sanitation systems and decentralized systems in unsewered areas by facilitating public-private partnerships to reduce environmental pollution.

1.1.4 Urban wastewater management in Bhutan

In the context of Bhutan, rapid urbanisation has resulted in increased demand for improved sanitation facilities (NEC 1998). By 2020, over 50% of Bhutan’s population is expected to live in urban areas generating more wastewater (Commission 1999). The increased wastewater demands a better sewerage network in the urban areas. Centralized treatment is often dedicated solely to the removal of common pollutants and does not aim to remove specific components of individual waste (Helmer & Hespanhol 1997). Otherwise, in unsewered urban areas, enhanced decentralized on-site wastewater treatment systems are crucial.

Wastewater management for urban areas in Bhutan introduced in 1996 consists of central wastewater treatment plants, primarily WSPs (Phuntsho et al. 2016). More recently, other forms of treatment systems have been introduced such as Moving Bed Biofilm Reactors (MBBR), Activated Sludge Plants (ASP), decentralised wastewater treatment system (DE-WATS) and Ecoline sewage treatment package plants, all of which are centrally operated. However, conventional "septic tanks" still serve 49.5% of towns and urban centres in Bhutan (Dorji et al. 2019). Conventional on-site sanitation includes community toilets, aqua privies, composting toilets, usually connected to a pit or "septic tank", some with soak-pits. (Sharma & Kazmi 2021). Although land treatment, i.e., soak-pits, are an integral part of on-site treatment, increasing urban development and loss of space mean soak-pits are often no longer connected or constructed. Besides, as urban density increases, there is a loss of permeable areas and increased risk to groundwater which may be extracted nearby or downstream for household and other uses.

The introduction of various dry or "eco" or composting toilets has been attempted in the past (PHED 2012). These waterless systems have not been taken up widely due to the individual perception or inconveniences attributed to the waterless systems. However, they can be found in rural mountain areas where cold weather and less water means they have been traditionally used for centuries.

In Bhutan, about 74.8% of households (HHs) have access to improved toilet facilities, i.e., flush toilets, ventilated improved pits (VIP), pit latrines with slab or composting toilets and the remaining HHs (25.2%) use unimproved toilet facilities (NSBB 2018). Most of these HHs do not have the treatment facilities necessary to protect them or the environment from untreated faecal sludge. In the urban areas of Bhutan, from the classified 33 towns enumerated in the survey, 57% of HHs in the towns are not connected to the main sewers which include HHs with septic tanks with or without soak-pits (Dorji et al. 2019).

About 49.5% of the residential buildings in the 33 classified towns in Bhutan have a "septic tank" and a soak-pit as the on-site treatment system of blackwater from the toilet (Dorji et al. 2019). Surprisingly, about 40.5% of the buildings have a "septic tank" only (without soak-pit). The remaining 10% use other forms of on-site treatment or dry pit latrines, which do not involve water flushing.

1.2 Problem statement and research motivation

1.2.1 The problem: inadequate wastewater management systems in urban Bhutan

Rapid urbanisation due to unplanned growth in Bhutan has resulted in increased infrastructures, urban population and density. Conventional central treatment plants are expensive to build in addition to the problem of limited space, due to many of Bhutan's towns being located along river valleys. Pollutant removal from conventional "septic tanks" is inadequate primarily due to its traditional design, followed with improper construction and operation. Complimenting septic tank, location of soak-pit is unsuitable due to limited space under the current urban settings.

A municipal survey of 33 classified towns of Bhutan indicated that 40.5% of the residential buildings in the urban towns have "septic tanks" only (without soak-pits) (Dorji et al. 2019). The on-site survey of the two selected pilot towns: Thimphu and Khuruthang, indicated that 56.2% of the buildings in Thimphu have "septic tank" only (without soak-pit). In contrast, 75% of the buildings in Khuruthang has "septic tank" only (without soak-pits). Particularly, considering the public WWTPs in all the municipal towns of Bhutan, 57% of the towns are not connected to a public sewerage system.

Due to insufficient capacity of "septic tank" and to reduce the cost of emptying, the greywater from kitchens and bathrooms in the unsewered areas are led directly into open surface drains. These unhealthy discharges lead to outbursts of disease in the settlements due to lack of access to adequate sanitation facilities (Helmer & Hespanhol 1997; NSBB 2017a). Wastewater pollutants percolate into the ground through shorter and longer pathways, where impurities are adsorbed and intercepted in the soil pores before reaching the groundwater and recipient streams. Given the rough hilly terrain in Bhutan, reliance on underground treatment by soil poses risks and further made worse by rapid urbanisation. Due to increased infrastructure developments, unsafely discharged wastewater may not percolate into the soil but may flow along the surface due to the lack of porous surfaces. Moreover, the limited available urban spaces are compacted to accommodate more infrastructure developments. Furthermore, the underground pathways may not be sufficiently long enough to provide the required filtering action before reaching the groundwater table.

Concerning the four Major Towns, 46.3% of the buildings have “septic tanks” without soak-pits, while only 39.9% had soak-pits. In the 16 District Towns and 15 Satellite Towns, these percentages were lower, at 15.7% and 30.7% respectively. Focusing on the two selected pilot towns: Thimphu City and Khuruthang Town were chosen to represent rapid infrastructure developments and 40% urban population living in Thimphu while Khuruthang Town was selected as the representative and emerging district towns of Bhutan. About 33.5% of buildings surveyed in Thimphu City used “septic tanks” and soak-pits, while 56.2% of the buildings were without a soak-pit and the remaining 10.3% use other disposal/ treatment systems. In Khuruthang Town, only 13.6% of the buildings surveyed had both a “septic tank” and a soak-pit, while 75% of the buildings had “septic tank” without a soak-pit and the remaining 11.4% use other forms of on-site systems including dry pit latrines.

While inspecting the buildings in the two towns, the set-back distance of soak-pits was less than 3 m (2.9 m for Thimphu and 2.2 m for Khuruthang) (Dorji et al. 2019) compared to the recommended 5 m minimum distance stated in urban and housing regulation (DUDH 2002). This set-back a distance of less than 5 m makes the location of soak-pit makes unsuitable under the current urban settings. Further, urban plots are increasingly unsuited to the construction of soak-pits since unplanned urban growth has led to dense settlements. Older plots are being split into smaller ones, combined with the unplanned nature of settlements results in emptying tankers have difficulty reaching HHs. In the absence of treatment plants in the district urban areas, the septages from tankers are unloaded into the downstream under hilly terrain landscape.

Discharges from a reported 40.5% of buildings without soak-pits in the 33 classified towns suggest that massive quantities of unsafe water are being discharged without sufficient treatment in terms of overflow, subsequently joining downstream watercourses. Water quality studies of the Thimphu river indicated that sewage wastewater pollution undermines the quality of streams and river downstream due to surface drainage seepage from urban areas (Giri & Singh 2013). Unsafe levels of Escherichia coli was found in the Thimphu river likely from septic tank leakages, wastewater treatment discharges and animal wastes (Kuensel 2017).

This indicates that reliance on private construction and operation of “septic tanks” while awaiting sewerage connections is not appropriate or desirable for the unsewered areas of urban Bhutan. Instead, institutional intervention and action are needed. Particularly following the development paradigm of Gross National Happiness, there is a need to value social benefits not only economic ones, and to protect national heritage sites and natural ecosystems which are vulnerable to continual wastewater discharges from inadequate on-site wastewater treatment. It may not necessarily be feasible to solve sanitary problems of domestic sewage flows generated in urban environments by using water consuming technologies that rely on conventional sewerage which entails carrying and transporting the suspended waste material away from the place where it was generated (Helmer & Hespanhol 1997).

Bhutan lacks municipal wastewater treatment plants for most of the urban and peri-urban areas. According to a survey conducted in 2016, 43% of the total HHs in the urban areas are connected to the public sewers, as shown in **Table 1.2**.

Table 1.2: Types of wastewater management systems in all the municipal areas of Bhutan (Dorji et al. 2019).

Classified towns with public sewerage system	Population (PHCB 2017)	WWTP type	Current WWTP load (MLD)	Buildings connected to sewer in the town	Approx. total PE currently connected	% population coverage	% of buildings
Total of the MT	161,392	WSP-3 MBBR-1 Ecoline-1	5.785	3266	42400	26.3	43.4
Total for the 8 classified towns including 4 DT	183,912	Ecoline-4 CST-1	7.539	3581	53365	29	43
Total for all non-classified towns	5,333	Ecoline-2 Oxidation ditch-1	-	31	940	17.6	26
Grand total with public sewerage	189,245	-	-	3612	54305	28.7	43

DT: District Towns, PHCB: Public & Housing Census of Bhutan, WSP: Waste Stabilisation Pond, MBBR: Moving Bed Biofilm Reactor, PE: Person Equivalent, CST: Community "septic tank"

A recent study evaluated centralized treatment systems as expensive, both conventional WSPs or imported package treatment plants (Dorji et al. 2019). Moreover, the establishment of WSPs in the city areas, apart from the costs, gave rise to the foul smell of the sewage, which inconvenienced the settlements living near the ponds. Further, the government lacks resources to fund wide-scale sewerage and large WWTPs, which are costly and complicated. Therefore, a transition option, providing an alternative on-site treatment upgrade to improve treatment efficiency and prevent environmental pollution would enhance public health and contribute to the country's economy under the pursuit of its unique development.

1.2.2 Motivation: the need for an improved alternative to the current conventional on-site sanitation treatment for urban Bhutan

With the increasing rate of urbanisation, decentralised wastewater management systems are already considered appropriate in many countries. Increased wastewater production is likely to put tremendous pressure on existing conventional treatment plants. Despite policies to connect households to centralised sewerage, the use of "septic tanks" is predominant in Bhutan and is likely to continue for years to come considering the rapid rate of urbanisation and lack of treatment options.

Based on national data from the municipal survey of 35 classified towns, a detailed on-site study was conducted in the two research pilot towns of Thimphu and Khuruthang. The on-site survey indicated the need to explore low-cost treatment options as alternatives or retrofit the existing on-site treatment, i.e., "septic tanks". Although most off-site treatment technologies benefit from economies of scale, anaerobic technologies tend to scale down quickly to the township or local level without remarkably increasing the unit cost. This makes anaerobic technologies suitable at the community level for inclusion in urban sanitation (Helmer & Hespanhol 1997). Compared to the often poor performance of individual units such as septic tanks, this improved on-site option can stimulate more disciplined operation and waste due to improved design.

We have highlighted the need for compact treatment systems which effectively treat wastewater and produce safe waste products, while also using locally available filter media. The application of locally available biofilters has not previously been implemented in Bhutan although large quantities of plastic wastes are generated in the municipalities, and industrial by-products such as slag filters and local materials such as bamboo are available. Thus, alternative and low-cost filter materials with suitable properties might be cheap fillings for ABF.

Waste plastic bottles constitute the majority of the non-biodegradable municipal wastes (NEC 2016a), making up 13% of the municipal solid waste in Bhutan (Phuntsho et al. 2010). In 2010, 40.3 tonnes per day of total municipal waste was generated in Thimphu alone, an enormous volume for a small country like Bhutan to manage, where there are no large scale recycling industries and limited landfill space. Due to their long life of plastics (Andrady & Neal 2009), it seems that waste plastics would make suitable biofilter media for the treatment of domestic wastewater.

Therefore, a pilot-scale UASB+ABF to treat blackwater effluents and greywater at the HH level is investigated. There are limited studies on organics and nutrients removal and production of biogas from combined black and greywater treatment in urban settings using ABFs with locally available biofilter media. Using UASB+ABF system could reap the twin benefits of using locally available materials as biofilters as well as reducing inorganic waste requiring disposal by municipalities and industries.

As presented above, anaerobic treatments have the advantage of requiring relatively less space, making them suited for use in urban contexts. The development of cost-effective anaerobic treatment technologies complemented by suitable pre and post-treatment can increase effectiveness further combined with the use of the locally available filter materials.

If the government can regulate and enforce effluent standards, the concentration of micro-pollutants, heavy metals, xenobiotics, etc., should be controllable. In this way, wastewater treatment could become an emerging industry envisaged in Bhutan in the coming years in terms of private services such as desludging and maintenance retrofitting. At the same time, the policy is yet to incorporate on-site sanitation treatment facilities as a long-term option under the context of the decentralised treatment system. Given the scope of treatment at the HH level, decentralised treatment of separate waste streams can be more specialised. Effective, low-cost retrofitted or new-build treatment to replace "septic tanks" can be applied in unsewered urban areas in the future and could gradually extend to the villages.

1.3 Thesis to be investigated

As already stated, the current health risks, limited urban spaces and municipal wastes mean that a treatment solution is needed, which provides more effective treatment than conventional "septic tanks" for the unsewered areas of urban Bhutan.

This Thesis will focus on the treatment of domestic wastewater only since in Bhutan; industrial waste is usually generally separated from residential and office areas.

The piloted treatment incorporates the use of locally available filter media: shredded waste plastic bottle strips, semi-charred bamboo beads, and industrial slags for the secondary treatment of mixed domestic wastewater, i.e., grey and black. These biofilters were selected based on the objective of adding value through the reuse of waste, while also reducing the burden on waste management and avoiding transport costs of non-local media.

The pilot treatment system described here is expected to be more cost-effective in the long run, since it uses locally available waste material as the biofilter unlike the designed and manufactured commercial filters. At the same time, saving limited space in the unsewered urban areas and having a low footprint at the community level.

In this study, two-staged treatment units, i.e., further filtration through waste plastic flakes in an ABF, performed better than single-stage reactors. Rather than as the primary treatment; as is usually stated in the literature; this study proposes the use of ABF for secondary treatment unit. The UASB unit treats organic-rich blackwater in the sludge bed, and sludge blanket since the influent lipids and detergents from kitchens and bathrooms can affect the sensitive methanogenic activity in UASB due to presence of suspended sludge bed and blanket. At the same time, the ABF captures the fluctuations in the dilute UASB effluents and solids along with the greywater. The lipids and detergents accumulated from kitchen and bathroom wastewater are degraded due to the better anaerobic process in ABF such as the presence of biomass on the surface of biofilter media and biosolids present in between the plastic media in ABF. A better gas transfer is achieved due to the existence of ABF's plastic matrix of light-weight plastics and better mass transfer.

This Thesis investigates the use of UASB reactors as the direct primary treatment of domestic sewage and secondary treatment of UASB effluent mixed with greywater by up-flow ABF using shredded plastic flakes as the biofilter medium. Additionally, pilot two-stage anaerobic treatment has not been studied for long-term treatment of domestic wastewater in Bhutan. Under ambient conditions in Bhutan, the combined mixed treatment of blackwater effluents and greywater in the ABF has not previously been investigated using local biofilters.

1.4 Purpose of the research

1.4.1 Research aim and objectives

Aim of the research

The research is aimed at improving the quality of the urban environment in Bhutan by reducing pollution from the discharge of poorly treated domestic wastewater effluent using an enhanced on-site wastewater treatment system in the two urban areas of Bhutan.

Objectives and scopes of the research

The following are the objectives of the research:

1. To assess the current domestic wastewater management practices in the urban centres of Bhutan, to document and understand the extent of the issues and challenges of conventional on-site sanitation system and explore suitable alternative options to address the challenges. The scope of this work includes collecting secondary data from municipal authorities and field survey to collect primary data from two towns of Thimphu (representing Major Towns) and Khuruthang (representing District Towns).

2. Evaluate through lab-scale and pilot-scale studies, the performances of an alternative on-site wastewater treatment system consisting of up-flow anaerobic sludge blanket (UASB) (in place of "septic tank" for primary treatment of blackwater) and anaerobic biofilter (ABF) for the treatment of combined greywater and primary effluent from the UASB (in place of the soak-pit/soil treatment) to verify compliance with national effluent discharge standards of Bhutan. Although several other treatment combinations are possible, the scope of this work is limited to sequential UASB and ABF to treat combined domestic blackwater and greywater.
3. Explore the potential of shredded waste plastic bottle flakes as a novel biofilter media to provide a large surface area per unit volume for the treatment of domestic wastewater by attached growth. This objective is also aimed at reducing the mounting waste plastic problem in Bhutan due to the absence of plastic recycling capacity. The scope of this work will be limited to waste plastic bottles; PET bottles shredded manually in regular square shapes, though, in reality, shredding machines produce varying shapes.
4. Explore other locally available materials for their potential use as biofilter media. The scope is limited to three different materials: semi-charred bamboo cut pieces, industrial slag and waste plastic strips.

1.4.2 The research questions

The following research questions are expected to be addressed in this Thesis.

- Is the two-step (UASB followed by ABF) anaerobic process effective to meet the national effluent standard in the treatment of domestic wastewater (combined blackwater and greywater) where the UASB replaces the "septic tank" while the ABF replaces the need for a soak-pit for disposal of the effluent to the soil?
- Are shredded waste plastic bottle flakes an effective biofilter media?
- Which of the other locally available low-cost materials in Bhutan were suitable biofilter media for wastewater treatment? How do their performances compare?
- How effective is the combined UASB and ABF using locally available biofilter media at removing nutrients (phosphorous and nitrogen) from domestic wastewater?

1.4.3 Research limitations

Technology cannot, however, be expected to solve every pollution problem. Generally, wastewater treatment systems are capital-intensive occupying space and require costly, specialized operators. Therefore, it is always preferable to investigate whether pollution can be minimized or prevented before selecting and investing in wastewater treatment technologies. A cost-effectiveness analysis needs to be carried out for any pollution control initiative and compared with the available alternatives.

The focus of the research is on providing a technical solution and limited to the verification of the proposed technology as an alternative to the prevailing septic tanks and designed to accommodate the greywater under the limited space in the current urban settings. Further, septic tanks are not designed to accept greywater under the current urban settings and even unregulated under the standard septic manual of Bhutan. In addition to technical verification of the proposed technology, logistics and financial criteria, reliable management by the local entity or local government is necessary for the system to function in a sustainable manner. Particularly, the management issues and challenges that currently affect septic tanks and which could affect the proposed system are not addressed in the current research.

The pilot investigation was carried out under controlled flow to achieve sufficient head for the up-flow of wastewater into the system. Practically, under gravity flow of the treatment system, there will be head losses since the flow will not be regulated like the flow from pumps. During the long-term operation of the treatment system, the BOD results could not be investigated over due to inadequate lab facilities. The laboratory column experiments were carried out under ambient conditions and without controlled parameters such as temperature. Considering the different temperature in different parts of Bhutan, temperature control was not incorporated in the current study. The non-availability of chemicals which are import in nature in addition to the COVID-19 pandemic limited the research investigations.

1.5 Thesis Outline

This dissertation contains seven chapters which include material published during the research tenure as a PhD candidate.

Chapter 1 provides a brief overall background and theme to the research, rationale for the study, research motivation, research problem, aim & objectives, scope, outline logic for the focus on anaerobic biofilters, and contribution to the existing research.

Chapter 2 provides a detailed literature review on global wastewater issues and national issues for Bhutan. It also includes a comprehensive review of anaerobic technology, mainly UASB and ABF, its evolution, benefits and challenges and strategies for further development are identified.

Chapter 3 presents the method and findings of a comprehensive survey conducted on the status of the sanitation system in the urban centres of Bhutan and detailed on-site survey at the household level in the two representative towns of Bhutan. The results of this chapter were published in Process Safety & Environmental Protection (Dorji et al 2019), which is titled: *Wastewater management in urban Bhutan: assessing the current practices and challenges.*

Chapter 4 evaluates the use of shredded waste plastic bottles as filter media for on-site WW treatment in urban Bhutan. Following a long-term study of the treatment (188 days), this Chapter evaluates the size effect of the media on the treatment efficiency of the system. The results from this Chapter were published in Process Safety & Environmental Protection (Dorji et al 2021), which is titled: *Exploring shredded waste plastic bottles as biofilter media for improved on-site sanitation in urban Bhutan*. The findings from this study were also presented during the International Conference of Challenges in Environment Science & Engineering (CESE 2018) in Bangkok, 4 - 8 November 2018.

Chapter 5 investigated a yearlong (still ongoing) pilot operation of a combined UASB and ABF treatment operated in Bhutan; its installation, commissioning, and operation. Despite its limitations, the potential as an alternative, improved on-site treatment for urban Bhutan is considered to be suitable for further exploration. A part of this Chapter is submitted to PSEP for review titled: *Improved on-site sanitation system using UASB and ABF: A pilot household study in Bhutan.* The result from this study was also presented during the Online International Conference of Challenges in Environment Science & Engineering (CESE 2020), Beijing, 7 - 8 November 2020.

Chapter 6 evaluates the use of local waste plastic bottles strips, industrial slags, semi-charred bamboo beads and commercial filter media for on-site wastewater treatment. A part of this Chapter is under preparation for publication and will be sent for review. It will be submitted to JEMA for publication titled: *Locally available materials as a biofilter for the secondary treatment of UASB effluent and greywater*.

Chapter 7 provides a summary of the significant conclusions from the research and provides recommendations for further improvement of on-site wastewater treatment using anaerobic technology and its potential.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This Chapter includes brief global wastewater issues with an emphasis on developing countries. Reviewing the wastewater at the worldwide scale and then following with the treatment systems in the developing countries, particularly on the development of suitable treatment systems in the unsewered urban centres of Bhutan is carried out. Acknowledging the issues and challenges of the current urban settings under the aftermath of rapid urbanisation, the review identifies the essence of decentralised on-site anaerobic treatment systems with an emphasis on ABF treatment using local biofilters. The principles of anaerobic digestion and its engineering applications are discussed such as UASB & its configuration and ABF reactors & its types. The post-treatments of UASB effluents are discussed since it entails further treatment. Due to the significance of biofilters in the developing countries, the literature covers the anaerobic treatment using biofilters, a discussion on different types of filters and their applications with a potential of application in Bhutan. The Chapter concludes with the significance of a two-stage UASB+ABF treatment model as an alternative to the improved on-site treatment system in Bhutan.

2.2 Global scenario of wastewater issues

By 2030, according to UN 2012, an additional 2.1 billion people are expected to be living in cities while producing billions of wastes every year including sludge and wastewater (Mateo-Sagasta, Raschid-Sally & Thebo 2015). With the massive production of faecal sludge, septage management is now gaining momentum in the developing countries where providing sewage treatment infrastructure is an expensive and complex matter. Surprisingly, most of the faecal effluents in the developing countries are discharged into the surroundings such as lakes and rivers (Corcoran 2010). This shows the majority of population both in urban and rural areas are at the risk of water-borne diseases from faecal sludge discharges in addition to the overflow of greywater into the open surroundings. Direct discharge of domestic greywater into ditches without any treatment affect the environment (Arifin et al. 2021). At the global scale, greywater constitutes 65% of the household wastewater (Vuppaladadiyam et al. 2019). However, given the scarcity of water in the developing countries, the essence of wastewater management cannot be overlooked since greywater constitutes the majority of the domestic wastewater and it has the potential for reuse in context to the resource scarcity in the developing countries.

2.3 Wastewater issues in developing countries

In most of the developing countries, domestic sewage is disposed of using conventional on-site sanitation systems such as septic tanks with or without water-flush toilets connected to centralised sewerage systems. The treatment of wastewater from traditional treatment systems relating to the centralised sewerage systems by far is well developed in the developed and industrialized countries (von Sperling 1996). However, treatment of domestic sewage from on-site sanitation systems in the developing countries are limited, and state-of-art-of-treatment technology had not been advanced due to little institutional developments and interventions. Further, the wastewater projects are not a priority due to poor perception of wastewater treatment, unlike water projects (Apau 2017). Comparatively, a very little has been published to date on the treatment of domestic sewage, especially using low-cost technology appropriate to the needs of the developing countries (Heinss, Larmie & Strauss 1998). It is in this interest to carry out the literature review to gather the information available on the treatment of domestic sewage with the view of learning what has been investigated and draw a context for this present research.

2.3.1 Wastewater treatment systems in developing countries

The wastewater management for the urban areas in the developing countries primarily comprises the centralised wastewater treatment system because it has been widely accepted as an efficient process for decades (Liu 2017). However, constructing municipal treatment plants are expensive and impractical for rural and some decentralized urban areas.

2.3.1.1 Centralised wastewater treatment

Majority of the wastewater treatment systems in the developing countries are centrally treated. Centralised sewage treatment system accounts for about 80% of the cost for the wastewater collection alone (Ahluwalia 2012). As the depth of the sewers goes on increasing, the sewer length increases, posing the higher risk of water contamination in the downstream due to low treatment efficiency and sludge contamination (Ahluwalia 2012). It is in this aspect that the central treatment plants are found not being able to cope with the stringent environmental regulation in the developing countries (Schories 2008). Surprisingly, strict environmental laws are enforced for a few centralised treatment plants in the developing countries, while the majority of the settlements are not even served by the primary treatment plants (Chernicharo et al. 2015).

Operational services of centralised wastewater treatment plants are limited (Chernicharo et al. 2015) since not every building under the municipality can be connected to the treatment plants. Central aerobic treatment systems provide a better quality of organic and nutrients removal; however, operation (O) and maintenance (M) costs are expensive due to aeration (Singh, Kazmi & Starkl 2015). Furthermore, they do not fully meet the criteria needed for a sustainable wastewater management strategy (Halim 2009), such as less production of waste sludge and minimal O & M costs. On the other hand, the natural systems require a larger area to treat the wastewater adequately, but their performances are limited in terms of organics and nutrients removal.

The management of central wastewater system in the developing countries are confronted with challenges. For instance, the wastewater accumulated in the sewers of centralised treatment plants is prone to natural disasters such as floods and earthquakes. Due to rapid urbanisation, inadequate wastewater management and implementation of complex centralised wastewater treatment technologies pad up to the challenges (Chirisa et al. 2016). Due to the complexity of the treatment system involved to solve the wastewater management problems; therefore, the centralised collection and treatment system are costly (Nasr & Mikhaeil 2015). Thus, with rapid urbanisation, more sustainable treatment options are required, such as decentralised on-site wastewater treatment system as an alternative to the complex inadequate centralised treatment system.

2.3.1.2 Decentralised wastewater treatment

On the other paradigm of the treatment system, the development of decentralised wastewater treatment leads to a self-regulating, self-maintained, and self-sustained facilities (Ahluwalia 2012). Under this treatment system, the benefits ensued is that the wastewater flows remain comparably small at any point, which causes only comparatively small environmental damage during the times of disruption or natural disasters, unlike the central treatment system where the disorder will have devastating consequences in terms of catastrophes. The robustness of the decentralised wastewater treatment is that under the local conditions of the urban areas, the treatment methods can be tailored specifically to their wastewater characteristics to meet the needs of the end-users (Ahluwalia 2012). This indicates decentralised treatment systems are flexible, adaptable and suitable at the household level under the unsewered areas in Bhutan, for instance.

On the contrary, the decentralised concept cannot be the solution to all wastewater management problems. There will be cases where central treatment plants are more appropriate and suitable. For example, decentralised systems might not have permanent operators, and it may not be frequently maintained and monitored, making compliance with regulation difficult. Still, benefits of decentralised wastewater management deserve greater attention, especially in smaller communities and scattered households at the periphery of the urban development in terms of sanitation services (Ahluwalia 2012) due to use of the inadequate conventional septic tanks.

Due to scarce financial resources of the government, decentralised treatment system as less resource-intensive would emerge as an appropriate treatment option as opposed to the centralised system (Massoud, Tarhini & Nasr 2009). In this context, environmental engineers are likely to design decentralised sustainable treatment systems. Therefore, in terms of economic benefits and sustainability, decentralised wastewater management is inevitable in developing countries (Lim & Kim 2014). Besides, sustainable wastewater treatment systems in developing countries should prioritize meeting local needs while remaining cost-effective to operate (Klarkson 2010). However, the objective of the decentralised system is to achieve adequate wastewater treatment and to protect the environment (Capodaglio 2017), especially considering the inadequacy of the on-site sanitation system. Following the literature discussion on the outcomes of decentralisation of sanitation systems, project the generally positive outlook for the decentralised treatment systems which are compatible with the settings of the urban and peri-urban areas in the developing countries, in particular under the rough and rugged terrain in Bhutan.

2.3.2 Wastewater treatment issues in developing countries

Sanitation coverage is inadequate in developing countries. According to the WHO Water and Sanitation Study, sanitation coverage in South Asian countries is estimated to be below 50% (WHO 2012). Unexpectedly, in most of the developing countries, sanitation problems feature low on the hierarchy of the issues encountered in comparison to health care, food supply and education (Massoud, Tarhini & Nasr 2009). For instance, water and sanitation receive a barely 6.1% in development fund compared to other sectors like health, education, transport, energy and agriculture (Kelkar & Seetharam 2019). Based on the low priority of the hierarchy of problems in the developing countries, inadequate sanitation systems are explicitly identified and surprisingly found to link with institutional and governance failures (Araral

2009). Nonetheless, sanitation problems are real that demands urgent and immediate attention due to its proximity to public health hazards and environmental pollution.

The lack of proper wastewater treatment infrastructures results in the low treatment of wastewater. It is likely that the low priority given to wastewater treatment infrastructures is due to the high capital costs and complexities involved while implementing the wastewater projects. While managing and implementing the municipal wastewater treatment projects; the adoption of technology had been determined by economics (Libralato, Ghirardini & Avezzù 2012). Other reasons for the lack of wastewater treatment infrastructures include a shortage of appropriate treatment technologies by not considering the local conditions of the set communities, low technical expertise, and most notably lack funds and public awareness and others. Expectedly, these factors give rise to the selection of an economically affordable treatment technology (Shrestha 2001) and to pursue its development. This affordability and outcome of treatment technology should lead to the realisation of the system, which includes the anaerobic treatment system at the core of the decentralised treatment system.

In terms of environmental importance, technical development, and financial capital, priorities for selecting wastewater treatment technologies differ between developing and developed countries, as shown in **Table 2.1**. The selection of centralised treatment technologies is proven efficient in solving the sanitation problems with the case in the developed countries (Kivaisi 2001). While selecting and implementing the treatment systems in the developing countries, considerations such as the technical capacity to fix the operational problems are often overlooked. Surprisingly, the failure of many treatment systems has resulted as the public oppose locating wastewater infrastructures near the community settlements (Massoud, Tarhini & Nasr 2009). This could be because the people are unaware of the adverse effect of improper sanitation built-up issues. When these improper sanitation build-up issues are overlooked in considering the improved treatment systems, as a result, it is common practice to discharge untreated wastewater directly into bodies of water (Senzia 2003; Shrestha 2001), which is often the case in the developing countries. Considering the scarcity of the current resources in the developing countries, WWTPs should gear towards to become more sustainable in terms of resource recovery from the municipal wastewater (Cardoso Chrispim 2021). As such, there is a great potential to expand wastewater treatment integrated with nutrient and energy recovery strategies in urban areas and stimulate creation of public regulations and policies by the decision-makers in wastewater sector for better operation and management.

Table 2.1: In both developing and developed countries, critical and essential criteria are used to select wastewater treatment technologies (von Sperling 1996).

Factor	Developing countries		Developed countries	
	Critical	Essential	Critical	Essential
Efficiency		x	x	
Reliability		x	x	
Sewage sludge disposal		x	x	
Requirements of land		x	x	
Impact on environment		x		x
Costs of operation	x			x
Costs of construction	x			x
Sustainability	x			x
Simplicity	x			x

2.3.2.1 Space constraints for on-site sanitation

In most of the developing countries due to the rapid growth in urban populace, space scarcity and financial constraints, constructing sewage treatments (STPs) is impractical (Sharma & Kazmi 2016). Inspite its wide application of conventional septic tanks, the system works as a low primary treatment unit with reduced treatment efficiency since its effluent still contains high concentration of pollutants (Coelho et al. 2004). Alternatives to the conventional on-site wastewater treatment systems pertains to the biofilm-based treatment of the septic tank effluents such as anaerobic filters. However, such alternatives comprise large-sized reactors which involve a high-cost investment in terms of land and construction. There are reports on the increased application of packaged pre-fabricated STPs for the treatment of domestic wastewater all over the world at the single household level owing to compactness than the other conventional treatment systems (Greaves, Thorp & Critchley 1990). In India, an anaerobic packaged-type on-site wastewater treatment system comprising two bioreactors (a septic tank and an anaerobic filter) was found to be adequately effective as the primary process of the treatment system (Sharma & Kazmi 2016). In Nepal, to reduce the space requirements, UASB fed with septic tank effluent and post treated with sand filters were be found to be compact and befits as low cost onsite sanitation system (Lohani, Khanal & Bakke 2020). While in Indonesia, community-managed DEWATS such as anaerobic baffled reactors (ABR) were practised due to dense settlements and limited space which constituted as an intermediate step and bridge to centralised sewerage and on-site sanitation in managing (Eales et al. 2013). Further, examples of conventional and new anaerobic treatment of wastewater treatment have illustrated several advantages including the space savings (Gavrilescu 2002).

2.3.3 Wastewater treatment options in developing countries

Depending on the size and density of the villages, municipal wastewater treatment systems are categorized using different parameters. However, they can be divided into two categories based on where they are used: on-site and off-site operation (Apau 2017).

2.3.3.1 On-site wastewater treatment systems

The conventional on-site sanitation includes: community toilets, septic tanks, aqua privies, bio-toilets, soak-pits and other on-site systems (Sharma & Kazmi 2021) such as pit latrines. The on-site system mainly comprises septic tanks and soak-pits or soil absorption fields, act as primary care units, eliminating a large portion of the organic matter that can be settled. The organic loads from the on-site domestic wastewater system are re-moved in the range of 30-40% (Sharma et al. 2016). Due to inadequate treatment of wastewater, the septages are transported to off-site treatment such as central treatment plants through the vacuum cleaning septic trucks. The loads are offloaded into the sewer utility holes and transported in the sewers connected to the treatment plants. The complete applications of septic tanks have drawbacks such as in the case of dense communities as septic system leachate has the ability to pollute the environment (Bremer & Harter 2012).

Pharmaceuticals and personal care products (PPCPs) as well as organophosphate flame retardants are also found in on-site wastewater systems including coliform bacteria, nitrates, and phosphorous, in addition to the usual contaminants (Conn 2010; Schaider 2016). As such, it seems effluents from on-site septic tanks are unsafe to discharge, which mandates an improved pre-treatment at household on-site. These hazardous discharges are in agreement with the 41% of buildings in the 35 classified towns without soak-pits in Bhutan.

The following are the characteristics of several popular on-site treatment systems in **Table 2.2**.

Table 2.2: Characteristics of a few on-site treatment systems (Apau 2017).

<table>
<tr><th>Technology for treatment</th><th>Application at community/household (HH)</th><th>Cost of construction</th><th>Construction complexity</th><th>Requirement of operational skill</th><th>Requirement of maintenance</th><th>Requirement of energy</th><th>Requirement of spatial</th><th>By-products added value</th></tr>
<tr><td>Ventilated improved pit latrine (VIP)</td><td>Especially for the community, but it can also be used at the HH level.</td><td>Low</td><td>Except in areas with a high groundwater level, construction is easy.</td><td rowspan="5">Low</td><td rowspan="3">Medium</td><td>None</td><td rowspan="5">Low</td><td rowspan="2">Soil humus</td></tr>
<tr><td>Vermicompost toilet</td><td>Both</td><td>Medium to high</td><td>Medium to high</td><td>Some variations necessitate less power.</td></tr>
<tr><td>Composting toilet</td><td>HH level, but it has the potential to be extended to include the entire population.</td><td>Low</td><td>High</td><td rowspan="3">None</td><td>Compost</td></tr>
<tr><td>Pour flush toilet</td><td>HH mostly, but also ideal for medium-density areas.</td><td>Low to medium</td><td>Low to moderate</td><td rowspan="2">High</td><td rowspan="2">-</td></tr>
<tr><td>Septic tanks (including Imhoff tanks)</td><td>HH, which is best suited to low- to medium-density regions.</td><td>High</td><td>High-skilled labor is required.</td></tr>
</table>

2.3.3.2 Off-site wastewater treatment systems

The traditional and highly mechanised off-site centralised wastewater treatment systems, which includes advanced wastewater collection, treatment, and discharge processes for large volumes of wastewater (Apau 2017). This wastewater management approach is most suitable in densely populated areas with limited land space. However, due to limited capital resources, building a centralized treatment system for small communities or peri-urban areas is a burden for the population in developing countries, necessitating the use of cost-effective treatment systems. Off-site treatment facilities are installed in decentralised settlements or centralised treatment systems for whole cities (Apau 2017). Off-site decentralised wastewater treatment systems are intended for small-scale use, mostly the low mechanised or natural methods. They are particularly well-suited to areas with incorrect zoning and sparsely populated rural and unsewered urban areas. Decentralised systems, on the other hand, allow for greater flexibility in integrating processes to meet treatment goals, address environmental issues, and ensure public health protection.

The standard systems of treatment used for municipal wastewater treatment off-site are described in **Table 2.3**. It should be noted that the treatment methods have been restricted to those that are most suitable for use in developing countries.

Table 2.3: Off-site wastewater treatment solutions that are currently used (Apau 2017).

System of treatment	Explanation	Salient features
Conventional aerobic processes		
Activated sludge process (AS)	Pollutants are decomposed by mechanically providing oxygen to aerobic bacteria that feed on organic material to be treated.	The complex process involving several mechanical and electrical components. Construction, processes, and maintenance all necessitated qualified staff. High expense, generates vast amounts of sludge that must be disposed of, but offers a high quality of treatment.
Aerated lagoons	Waste stabilisation pond equipped with mechanical aeration.	The majority of oxygen is supplied by aeration systems, making it more difficult to operate and incurring higher O&M costs.
Oxidation ditch	Similar to a stabilisation pond, but with an oval-shaped channel and aeration.	The energy demand is higher, but the land requirement is lower than that of a stabilization pond. Service necessitates less experience.
Trickling filter	A loose bed of stones or other coarse material moves over the sewage, and a biofilm on the ground surface decomposes organic material in the sewage.	The biofilm's oxygen needs are met by the atmosphere. Has moving parts that break down often in developing countries.
Rotating biological contactor (bio disk)	It is made up of a series of thin vertical plates that provide bacteria with surface space to grow on.	Rotation exposes plates to air and wastewater, with around 30% immersion in sewage. While highly effective, there are frequent breakdowns.
Anaerobic processes		
Up-flow anaerobic sludge blanket reactor (UASB)	A blanket of bacteria absorbs the polluting load in an anaerobic process.	They thrive in tropical and subtropical climates. There is little sludge generated, and no oxygen or power is required. Typically necessitates effluent post-treatment.
Natural treatment processes		
Waste stabilisation ponds (WSP)	A series of broad surface area ponds that are connected to one another. Ponds have different depths for different purposes.	The action of sunlight, which encourages algal growth and thus provides the oxygen required by bacteria to oxidize organic material, is critical for treatment. Due to low building, operation, and maintenance costs, it is especially well suited to developing countries. Suitable for treating pathogenic material.
Constructed wetlands (CW)	The artificial treatment system was designed and built to mimic biological processes found in natural wetland ecosystems. It boosts biochemical functions including filtration and washing in the ecosystem.	The treatment is the soil matrix, precisely the soil-root interface of the plants. There is no need for oxygenation in mechanical devices. It is appropriate for developing countries. It takes a long time to assess the best treatment capacities.
Land treatment (soil aquifer treatment - SAT)	Sewage is applied to a soil media under controlled conditions.	If the capacity is not surpassed, the soil matrix has a high capacity for treating conventional domestic wastewater. For all contaminants, this is not feasible. Contamination of soil, groundwater, and plants is more likely.

2.3.3.3 Septic tank and soak-away systems

Formal scientific literature relating to septic tank design and performances are limited since the researches on the conventional treatment systems have taken a back seat. Still, a large body of information on these subjects exists in the trade literature for timely implementation. Septic tanks are the most used unit for pre-treatment of domestic wastewater in on-site applications in the developed and developing countries. A thorough review and discussion on design and performance of the septic tank and soak-away system are published in an On-site Wastewater Treatment Systems Manual by the United States Environmental Protection Agency (USEPA) (USEPA 2002).

The septic tank is a covered, water-tight rectangular, oval, or cylindrical vessel that is usually buried in the earth. Compartmentalized tanks or tanks placed in series are reported to provide better suspended solids removal than single-compartment tanks alone (Capodaglio 2017) due to increased detention time. Primary treatment in the septic tank is due to retention of wastewater under quiescent conditions. Solids and scum from the influent wastewater are separated in the tank by settling or floating of solids in wastewater. A microbial community of anaerobic micro-organisms present in the tank partially digests solids and scum, and to a lesser extent, suspended organic materials in the liquid phase. Under partial anaerobic conditions, solids and colloidal materials are hydrolysed and acidified, producing volatile fatty acids (VFAs) that are partially converted to CH_4 and exit in the septic effluents along with the flocculent wastes as floating scum layer.

Digestion of scum and solids can result in the reduction of up to 40% of retained material; however, a slow accumulation of sludge is observed in the tank over between 2 - 20 years, depending on loading (USEPA 2002). Thus, the anaerobic conversion of organic matter occurring in septic tanks yield to the low conversion of organic components due to sludge accumulation at the bottom and scum layer on the surface reducing the active volume and reducing hydraulic retention time (Capodaglio 2017). Septic tanks are reported to remove 60-80% of non-soluble material in domestic wastewater (USEPA 2002). BOD removal is typically in the order of 30 - 50% for a septic tank operating at a 48 h (Nasr & Mikhaeil 2013). Actual performance of the septic tank depends on the ambient temperature, using HRT and presence of inert or micro-organism-inhibiting chemicals in the influent (Foxon et al. 2004). This indicates the conventional treatment systems are unable to remove the organics and nutrients using septic tank-soak-pit systems which are predominantly practised in the developing countries.

After undergoing the partial anaerobic digestion, the solids settled down at the bottom chamber of the septic tank. While, the septic effluents are discharged into the vadose zone via an engineering soil dispersal system (SDS): soakaways, percolation trenches/leach fields, mound soil systems, and drip line systems (Somlai-Haase, Knappe & Gill 2017). In the SDS, a clogging zone forms at the infiltrative surface during the percolation of the septic tank effluents over time. Initial clogging occurs on the infiltration surface of undergrounds soils due to suspended solids, organic matter, and chemical residues getting accumulated on the infiltrative surface, which results in the state of potentially saturated conditions. This saturated conditions of initial clogging stage develop into the ponding of septic tanks effluents at the infiltrative surface of the underground soils. As a result, the infiltration flow of effluents are opposed and intensified leading to a development of a mature biological clogging zone (also known as a microbial biomat) which facilitates significant degradation and reduction of contaminants present in wastewater before it infiltrates the underlying groundwater bodies (Somlai-Haase, Knappe & Gill 2017). However, the limited urban space in Bhutan and available limited spaces are compacted for the expansion of infrastructures making the location of soak-pit unsuitable under the current urban settings.

2.4 Wastewater treatment and management issues in Bhutan

2.4.1 Public wastewater treatment and management systems

The municipalities manage the wastewater treatment systems under the purview of government nodal agency: Ministry of Works and Human Settlements (MoWHS). Owing to the construction costs, the initial and prominent treatment systems used were wastewater stabilisation ponds (WSPs). However, with rapid urbanisation confronting the limited urban spaces, the modular systems are adopted upon the approval of the government. Four out of 35 classified towns use Ecoline treatment system (refer to **Chapter 3**). For the settlements in the periphery of the capital town – Thimphu – the treatment system such as Moving Bed Biofilm Reactor (MBBR) was established to meet the sanitation needs of the public with the establishment of Activated Sludge Process (ASP) system. Also, DEWATS is used in Samtse since the town lacked the public sewerage system. Having 20% of the total urban population in Bhutan accessible to the public sewerage system, more than three-quarters of the total population is still relying on the conventional septic tanks

Currently, less than 19.7% of the total urban population in Bhutan has access to public wastewater treatment systems (Dorji et al. 2019). Therefore, the problems and challenges of the existing infrastructures in urban Bhutan are acknowledged and crucial to explore alternative options. Construction of public sewerage system requires significant capital investments for both sewer networks and treatment plants beside costs associated with the annual operating and maintaining that plants for which government lacks financial resources to provide public wastewater treatment services for all the urban areas in Bhutan. Hence, the provision of these services is prioritised through the needs in the towns and provide services accordingly. The survey indicated the existing waste stabilisation ponds (WSPs) are cheaper; however, has a larger footprint unlike the expensive imported modular Ecoline treatment systems with higher maintenance and operation costs but having a lower footprint. Although the effluents from Ecoline are expected to be better and superior compared to the WSPs, such technology is un-affordable for Bhutan. Also, the use of a moving bed biofilm reactor (MBBR) is expensive and lack the expertise to operate and maintain the treatment system. The use of activated sludge process (ASP) system involves aeration which requires electricity. Even the decentralised wastewater treatment system (DEWATS) is costly and occupy public space due to the require-ment of compartmentalised treatment series despite the use of cheaper local materials.

2.4.2 Issues and limitation of wastewater treatment systems

About 79.3% of the entire population of Bhutan depends on the conventional septic tanks as the on-site sanitation system (Dorji et al. 2019). However, usually, septic tanks are confronted with unsatisfactory performance (30 - 50% COD removal and 60% TSS) (Capodaglio 2017). Moreover, due to the rough terrain of the urban centres in Bhutan, urban lands are insufficient to accommodate the septic tank. In contrast, urban spaces are unsuitable for the location of soak-pit as appeared during the on-site survey of the two towns (refer to **Chapter 3**). In the absence of soak-pits, the septages were leaked into the surroundings risking the public's health.

Moreover, the septic tanks were constructed without the technical specifications in which the case the quality of septic tanks are inferior of its kind. This corroborated with the leakages of septages from the septic tanks often observed during the on-site household survey. It is in this context; the household owners responded to the issue of leakages as the top priority concerning the implementation of conventional on-site sanitation systems.

Due to the conventional design of septic tanks, the tanks serve as a mere containing unit where the septages flow into the surrounding without enough treatment. The septages are desludged into nearby streams in the absence of treatment system as noted from the municipal authorities. Even desludging truckers are not available for its services in some of the urban towns. Though the status of sanitation does not seem grave; however, an inadequate treatment system is a concern since the majority of the populace depend on septic tanks since left without options. The functions of septic tanks are aggravated with the rapid growth of infrastructures where the ground surface is compacted, which becomes unsuitable for the location of soak-pits. In a mountainous country like Bhutan, urban space for the establishment of the septic tank is a challenge. This situation prompts the need for alternate on-site sanitation system, particularly for the unsewered areas in the urban centres of Bhutan. In this context, the anaerobic treatment systems befit the context of inadequate development of on-site sanitation systems.

Different methods/processes/facilities used for the treatment of sewage at on-site sanitation are mentioned in the literature. To the best of the knowledge, countries in Asia seems to be at the forefront in the development of treatment methods for sewage with Japan taking a pivotal lead guided by treatment goals and objectives (Misaki & Matsui 1996). Despite the remarkable progress, the costs and complexity of the treatment technologies impede their use in Bhutan unless the technologies are modified to suit the local needs and made simpler in applications. For instance, low cost in capital and operating costs for the treatment systems are emphasized while also ensuring compatibility with the expertise available in the particular country (Heinss, Larmie & Strauss 1998). These instances are limited in context to the existing treatment systems in Bhutan (Dorji et al. 2019). The limitation of the current wastewater treatment systems includes the recurring O & M, which lack expertise and funds. Also, the existing treatment systems do not incorporate future treatment capacity, considering the increased populace in the years to come.

From the literature, the use of waste stabilisation ponds or lagoons is evident as the simple and low-cost technologies for the treatment of supernatant after primary treatment (Gruchlik, Linge & Joll 2018). Whereas lagoons are used since it is well developed and already in use in the developing countries, the shortfall is the need for a pre-treatment system to reduce the strength of the wastes significantly before using the pond system (Heinss, Larmie & Strauss 1998) adding complexities to the existing treatment systems. However, the development of low-cost technology for the sewage treatment in Bhutan grossly lacks behind that of the conventional treatment technologies used due to lack of institutional capacity and intervention from the public agencies and initiation from private sectors.

2.5 The emergence of anaerobic treatment systems

The anaerobic treatment is considered as one of the oldest technologies for wastewater stabilisation and had been applied since the end of the 19^{th} century primarily for the treatment of HH wastewaters in septic tanks, treatment of slurries in digesters and the treatment of sewage sludge in municipal treatment plants (Gavrilescu 2002). With the first anaerobic digester built-in, 1859 by a leper colony in Bombay, India, the use of anaerobic reactor began (Abdelgadir et al. 2014). In 1890, Mouras developed and implemented the "septic tank" concept in Exeter, England, which is considered to be the first application of the anaerobic process for the treatment of domestic wastewater (Fdz-Polanco, Pérez-Elvira & Fdz-Polanco 2009). After that, in the 1930s, anaerobic digestion gained academic credit through scientific investigation (Abdelgadir et al. 2014). Thus, the septic tanks embody the first generation of the invention of the anaerobic bioreactor (AB).

During the energy crisis in the 1970s, stimulated the growth of cost-effective treatment systems such as the field of anaerobic treatment. The inception of the second generation of "high rate" reactors – in which HRTs are uncoupled from SRT – gave rise to the worldwide acceptance of the anaerobic technology as a cost-effective alternative to the conventional wastewater treatment systems (Gavrilescu 2002). Therefore, the anaerobic digestion gave a substitute to the energy crises, and today the process is increasingly used due to the emergence of fixed-bed biomass systems to treat sewage (Foresti, Zaiat & Vallero 2006). In the late 1970s, the UASB process was developed to represent the second generation of the anaerobic bioreactor (Lettinga et al. 1980). In this case, an improved development included the incorporation of the three-phase separator – gas-liquid-solid separator (GLSS) – in UASB to prevent the wash-out of sludge. The early works of anaerobic wastewater treatment can be found in (Seghezzo et al. 1998).

The third generation of the anaerobic bioreactor, namely expanded granular sludge bed (EGSB) and internal circulation (IC) was developed on the underlying foundation of the second-generation AB. The improvement in the third generation of AB was the increased flux which enabled the partial expansion (fluidisation) of the granular sludge bed while enhanced the wastewater-sludge contacts in addition to the separation of small inactive, suspended solids (flocs) from the sludge-bed. This development of the third generation of AB indicated that the (1) process parameters: up-flow velocity (V_{up}), sludge retention time (SRT) and hydraulic retention time (HRT), and (2) bioreactor structures (inner components), are the two most essential aspects for the cultivation of microorganisms in the anaerobic bioreactors (Abdelgadir et al. 2014).

2.5.1 Anaerobic biological degradation

Anaerobic processes are potent natural decaying processes where every organic matter are degraded to support civilization in terms of environment and health (Mgana 2003). The anaerobic treatment of wastewater is an intricate biological process involving several groups of micro-organisms in the complex inter-biological conversion (Cakir 2004). Anaerobic treatment systems are usually used for sludge treatment due to the lack of oxygen (O_2); however, using industrial wastewater to produce biogas is uncommon (Sattler 2014). Anaerobic biological degradation involves a sequential series of metabolic reactions whereby complex organic matters are degraded to form methane (CH_4) and carbon dioxide (CO_2) as the primary end-products, as shown in **Figure 2.1**. These metabolic reactions are referred to as hydrolysis, acidogenesis, acetogenesis and methanogenesis (Henze et al. 1997; Tchobanoglous, Burton & Stensel 2003).

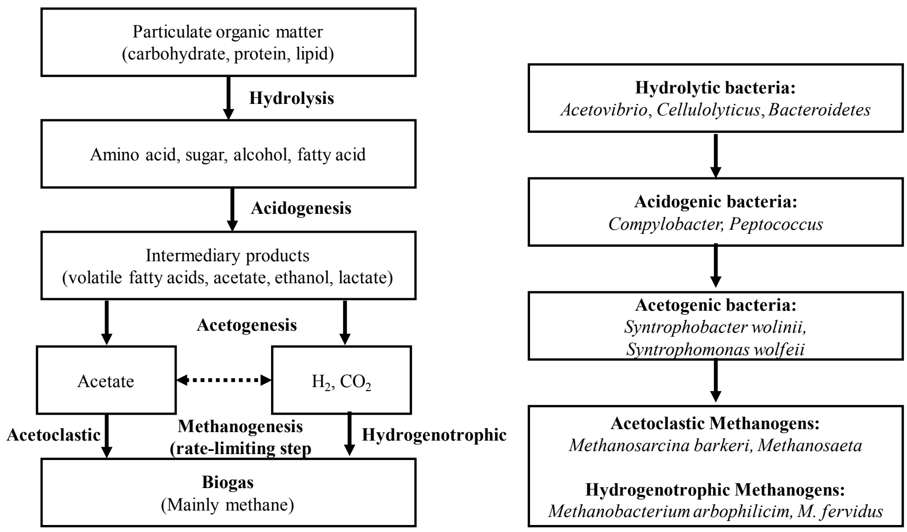

Figure 2.1: Carbon flow inside the anaerobic digester and bacteria involved in different stages of anaerobic digestion (Goswami et al. 2016).

Hydrolysis is the process where complex organic substrates, such as carbohydrates, proteins and fats are converted into sugars, amino acids and complex fatty acids (Tchobanoglous, Burton & Stensel 2003). Starch particles cannot be microbiologically degraded unless they are hydrolysed by enzymes to form soluble carbohydrates. The factors namely temperature, pH, particle size and concentrations of intermediate products influenced the rate of hydrolysis. Under anoxic and anaerobic conditions, hydrolytic enzymes for hydrolysis were found suppressed, and that starch hydrolysis was linear with biomass concentration (Goel et al. 1998). To obtain equilibrium between loss of enzymes and production of biomass at steady state, the recycling of floc bound enzymes within the sludge system was proposed (Tchobanoglous, Burton & Stensel 2003), to enable the retention of sludge bed in the system.

Acidogens ferment the basic structural blocks from hydrolysis into simple organic acids, alcohols, hydrogen, and carbon dioxide is referred to as acidogenesis. The further conversion of these blocks into acetate, carbon dioxide and hydrogen by acetogens are referred to as acetogenesis. The most formed acid is acetic acid which is biologically degraded to acetate besides other typical fermentation products such as propionate, butyrate, succinate, and lactate (Tchobanoglous, Burton & Stensel 2003). The final step of the anaerobic biological degradation is referred to as methanogenesis. It is the process whereby methanogens convert the end products from acetogens such as hydrogen, formate and acetate are converted to methane and carbon dioxide.

For the anaerobic system to operate at steady state in its entirety, a dynamic equilibrium is required between the acidogens, acetogens and methanogens. Acetogens produce hydrogen (H_2) and in turn, used by the methanogens giving rise to the low partial pressure of H_2. Otherwise, the high partial pressure of H_2 accumulation inhibits the growth of acetogens. When the system is operating at steady state, the interspecies H_2 transfer process provides a dynamic equilibrium between non-methanogenic and methanogenic bacterial communities to enhance the anaerobic digestion process (Tchobanoglous, Burton & Stensel 2003).

To prevent the upset of anaerobic digestion process and their central role in methanogenesis, propionate, acetate and hydrogen are probably the most important intermediate products in anaerobic digestion and therefore the key process indicators (KPIs) in the system (Labatut & Gooch 2014). During the anaerobic digestion of methanogenesis, about 64% of the methane is generated from acetate, while the remaining 36% is produced from hydrogen (Batstone et al. 2002). Propionate is an essential precursor of acetate and hydrogen with approximately 30% of the electron flow and directly related to methane production route through propionate (Jeris & McCarty 1965). Furthermore, propionate, acetate and hydrogen are more sensitive to upset of anaerobic digestion process than biogas production. As opposed to VFAs, pH, biogas production, and methane content are a result of process disturbances, rather than a direct cause (Labatut & Gooch 2014). This suggests it is not recommended to use these parameters as leading indicators of digester upsets. Most of the system upsets occur because of inadequate operational management and lack of process control (Labatut & Gooch 2014).

For decades, the underlying theory of anaerobic digestion has been established; however, a great deal of current research is oriented towards the optimization of anaerobic digestion under varied digestion conditions (Meegoda et al. 2018). Much needs to be done in evaluating the technological effectiveness with domestic wastewater (DWW) under ambient conditions, where the potential for DWW treatment need to be energy-producing, cost-effective and to meeting environmental discharge requirements (Stazi & Tomei 2018). Like any other wastewater treatment process having benefits and drawbacks; however, choice of treatment processes are often influenced by the site-specific conditions (Switzenbaum 1995). For instance, use of site specific blast furnace dust (BFD) improved the anaerobic digestion in UASB reactor due to the synergistic effects of Fe and C ions undergoing micro-electrolysis in the anaerobic system while regulating the sludge (Yang et al. 2019). Often, this use of site-specific material appears as the engineering practice operating before basic science to resolve the sanitation challenges. Therefore, this imply that the proper role of anaerobic digestion process is not always clear in terms of waste treatability, treatment goals and by-products usage.

2.5.2 Benefits and drawbacks of the two-phase anaerobic digestion process

In the development of sludge-bed formation and retention of biofilm on the carrier materials, the acidogenesis appears to occur more frequently than the methanogenesis leading to the accumulation of inhibitory VFAs (Goswami et al. 2016). This inhibition led to the development of the two-phase anaerobic digestion processes where biogas production is higher than in a conventional anaerobic digester. The high biogas production is attributed due to the improved removal of organics ascribing to the removal of H_2 produced during the first phase of the anaerobic digestion process (Guerrero et al. 2009). Besides, the separation of phased digestion resulted in the reduction in the overall size of the reactor.

However, the concept of two-phase anaerobic digestion appears to have become outdated (Kalogo & Verstraete 1999). Now the preference seems for the idea of two-stage digestion due to the slowdown of granulation process in the first reactor while influencing negatively in the second reactor of the two-phase anaerobic digestion process (Lettinga & Hulshoff Pol 1991). Dividing the anaerobic reactions into two reactors might not improve the stabilisation of the anaerobic digestion process or the removal of the soluble organic matter unless the growth of microbes is a primary priority. This partly explains why the two-phase reactor configuration has not reached the level of development to that of the conventional one-phase reactor (Donoso-Bravo et al. 2019). Thus, the use of a two-phase anaerobic digestion process for the municipal solid wastes is in decline (De Baere & Mattheeuws 2013). This indicates the two-stage anaerobic treatment leads over the two-phase anaerobic digestion process.

Based on the foundation of UASB technology being the robust technology while enhancing the removal efficiency, at least two-stage reactors are suggested for the treatment of raw domestic wastewater and found attractive in particular (Kalogo & Verstraete 1999). This is because, under the two-phase of acidogenic and methanogenic, it affects the transfer of interspecies H_2 from acidogens to methanogens due to phase-separation (Kalogo & Verstraete 1999). In this context, it appears two-stage treatment of wastewater is suitable for the on-site anaerobic treatment of domestic sewage in Bhutan.

2.6 Anaerobic treatment of domestic sewage

Unlike the aerobic treatment of sewage such as activated sludge processes, trickling filters, ponds, and oxidation ditches; anaerobic treatment of domestic wastewater is a more recent approach to domestic wastewater treatment in context to Bhutan, which draws the understanding of complex sewage features.

2.6.1 Complex sewage characteristics

Domestic wastewater typically has fairly low-strength with organic content ranging from 250 - 1000 mg COD/L (Seghezzo et al. 1998). However, wastewater is a complex substance comprising a mixture of proteinaceous, fatty and carbohydrate components in particular and soluble forms, and inert and refractory components (Henze et al. 1997). The presence of a high fraction of particulate COD, moderate biodegradability of various COD fractions, low strength character with multiple concentrations of nutrients and its relatively low temperature make the domestic sewage to be categorised as 'complex' wastewater (Gomec 2010). The typical composition of municipal wastewater is shown in **Table 2.4**.

Table 2.4: Typical composition of untreated municipal wastewater (domestic wastewater including constituents added by commercial, institutional and industrial sources) (Kaetzl 2019).

Contaminants	Unit	Concentration		
		Weak	Medium	Strong
TSS	mg/L	120 - 250	210 - 400	400 - 600
VSS	mg/L	95 - 200	160 - 320	315 - 480
BOD_5	mg/L	110 - 230	190 - 350	350 - 560
COD	mg/L	250 - 500	430 - 750	740 - 1200
TN	mg/L	20 - 30	40 - 60	70 - 100
NH_3-N	mg/L	18 - 20	30 - 45	50 - 75
NO_3-N+NO_2-N	mg/L	0 - 0.6	0 - 0.6	0 - 0.6
TP (inorganic)	mg/L	3	5	8
TC	No. /100 mL	10^6 - 10^8	10^7 - 10^9	10^7 - 10^9
FC	No. /100 mL	10^3 - 10^5	10^4 - 10^6	10^5 - 10^8

TSS: Total Suspended Solids; VSS: Volatile Suspended Solids; BOD: Biological Oxygen Demand - 5 Days; COD: Chemical Oxygen Demand; TN: Total Nitrogen; NH_3-N: Ammonia Nitrogen; NO_3-N+NO_2-N: Nitrate and Nitrite Nitrogen; TP: Total Phosphorous; TC: Total Coliform; FC: Faecal Coliform

In the digestion of complex domestic wastewater, the initial hydrolysis is the rate-limiting step because the complex suspended particulates in sewage need to be converted into simple sugars, amino acids, VFA and H_2, as a precursor to the sequential steps of the anaerobic digestion process. Particularly, suspended solids in wastewater are hydrolysed slowly relative to other degradable components of the wastewater; therefore, tend to accumulate in the reactor, thereby decreasing the active reactor volume for sludge (Kalogo & Verstraete 2001). It is in this aspect the management of suspended solids associated with the domestic wastewater is the complex and critical factor in the design of a system for anaerobically treating domestic wastewater (Lettinga et al. 1993).

2.6.2 Characteristics of domestic sewage in Bhutan

A very little had been done to date to characterise faecal sludges from on-site sanitation system in Bhutan compared to the developments in the developed countries. This inadequate characterisation of domestic sewage is attributed to routine assessments of sewage and treatment plants, unlike the mandatory requirements in the developed countries monitored by the institutions with strict regulations. In context to Bhutan, there is an absence of selected variables on which assessment of domestic sewage can be based. There is a lack of standard methods of analysis such as per capita quantities of sewage which would influence the characterisation of sewage. The investigation carried out in this study is a head start to standard the performance and improvement of the treatment systems in Bhutan.

2.6.3 Per capita quantities of sewage

Determining the quantities of sewage generated is a prerequisite in the planning and design of treatment and disposal facilities. Surprisingly, data are unavailable on per capita quantities of sewage generated in context to Bhutan, which could impede the further development of improved on-site sanitation systems. On the other hand, from region to region, per capita quantities are reported to vary widely from region to region (Strauss, Larmie & Heinss 1997). Though geographically different, the daily per capita on different types of sewage are provided concerning Ghana as shown in **Table 2.5** to indicate per capita quantities sewage in the under developing world to facilitate the optimised design of on-site sanitation system and facilitate operation and maintenance during the implementation of the treatment system.

Table 2.5: Daily per capita BOD, TS, TKN quantities of different types of faecal sludges (Doku 2002).

Parameter	Septage	Public toilet and bucket latrine sludge	Fresh excreta
BOD (g/cap.day)	1	16	45
TS (g/cap.day)	14	100	110
TKN (g/cap.day)	0.8	8	10
lpcd	1	2 (includes water for toilet cleansing)	1.5 (faeces and urine)

As indicated in the table, since more water is used in flushing water closets than in public toilets and restrooms, the daily per capita volume for sewage is relatively low. With a marginal variation in the components of domestic wastewater primarily related to chemicals used in the households (HHs) and personal care products (PCPs); however, the concentration of contaminants is significantly different between developed and developing countries depending on the water consumption and waste generation as shown in **Table 2.6**. This low strength characteristics of wastewater in the developing countries should not constrain the treatment system due to the low strength of suspended solids during the direct treatment of domestic sewage.

Table 2.6: Comparative values for raw wastewater constituents per person per day (g/person/d) (Kaetzl 2019).

Reference	Per capita loads (g/person/d)				
	COD	BOD_5	TN	TP	TSS
Typical value in developing countries	100	50	8	1	60
USEPA*	115 - 125	35 - 50	6 - 17	1 - 2	35 - 50
Household wastewater, Sweden	135	73	14	2	66
Household wastewater, Uganda	-	55 - 69	8.2 - 14	1.1 - 1.6	41 - 55

*USEPA: United States Environmental Protection Agency

2.6.4 Direct treatment of raw domestic sewage

Wastewater from the conventional centralised sanitation systems combines all wastewater resources accumulating to large wastewater volume with diluted organic and nutrient concentrations which is unfavourable for energy and nutrient recovery (Gao et al. 2019). However, source-separation of domestic sewage at on-site treatment systems allow targeted treatment of source-separated wastewater such as blackwater, recovery and reuse of resources and control of pollutants in the areas close to the sources (Eshetu Moges, Todt & Heistad 2018). Notably, better treatment of human urine comprising a combination of treatment processes encompasses removal of phosphate and ammonium by struvite precipitation and a biological process to remove organic pollutants and nitrogen (Biswas, Rana & Meers 2020). To enhance the treatment of septic effluents from the conventional septic tanks require additional reactor system which incurs additional costs and spaces. Thus, the direct anaerobic treatment of raw domestic sewage ensures the following benefits (Kalogo & Verstraete 1999):

- Generation of effluent with quality for irrigation.
- Reducing the poor effect of suspended solids in the UASB reactor.
- Trapping of energy from organic waste in an environmentally friendly way.
- Prevention of odours from the anaerobic effluent.
- Improvement of a compact system for post-treatment.

Although published literature on the use of anaerobic digestion for the direct treatment of domestic sewage is limited, nevertheless, published works indicated that the direct treatment of domestic sewages is feasible through the use of anaerobic digestion (Gomec 2010; Lettinga et al. 1993). Limited research has been conducted to evaluate the application of anaerobic digestion process for the treatment of blackwater (Gao et al. 2019). Few studies reported a wide range of COD removal efficiencies (61 - 80%) and percentage of methanisation (39 - 60%) (Gao et al. 2019). These variations are attributed to the use of varied reactor configurations and the operating conditions adopted (psychrophilic vs mesophilic). The reactor configurations are explained in the subsequent chapter to provide alternatives to the wastewater treatment. Thus, considering the predominant use of conventional septic tanks at the buildings in the urban towns of Bhutan, providing the direct primary treatment of raw domestic sewage (excluding greywater) through the anaerobic digestion in the UASB suit the needs of improved on-site sanitation systems in Bhutan followed by treatment of mixed domestic sewage effluents and greywater in the anaerobic biofilter (ABF).

2.6.5 Direct treatment of mixed domestic sewage effluents and greywater

To enable the biological treatment of greywater through an optimal C: N:P ratio, the UASB blackwater effluent is mixed with the greywater to avoid the deficiency of both macro-nutrients and trace nutrients in the sludged bed of ABF (Friedler & Hadari 2006). A mixture of blackwater effluent with greywater has a balanced C: N:P as suggested by (Tchobanoglous, Burton & Stensel 2003) to enable the biological anaerobic treatment of mixed domestic wastewater for safe discharge into the surroundings. However, the literature on the treatment of blackwater effluents and greywater mixed are limited. The use of concentrated greywater did not generate enough methane from the UASB reactor, possibly due to the presence of surfactants in greywater (Elmitwalli et al. 2007). On the other hand, dilution of greywater had a positive effect on the UASB reactor (Boyjoo, Pareek & Ang 2013). On the contrary, the treatment of faeces, together with the greywater increased the nutrients loads considerably to generate more biogas by installing lower UASB reactor volume (Shoa, Barjenbruch & Wriege-Bechtold 2017).

Separating blackwater effluents, greywater treatment systems of varying complexities are used around the world (Boyjoo, Pareek & Ang 2013). It is cumbersome to suggest the best greywater treatment system since each system has its benefits and drawbacks, while each country has its preferences and expertise. However, case studies show that those natural and biological systems are currently being opted as the core treatment for greywater, especially for reuse (Boyjoo, Pareek & Ang 2013). For instance, filtration is used as the primary treatment of greywater in India, where, despite its low quality, the effluents are considered satisfactory for toilet flushing or irrigation (Mandal et al. 2011). This filtration is one of the feasible options for the greywater treatment with the effect of different filtration media on the removal efficiency if clubbed in series with other treatment systems (Ghaitidak & Yadav 2013). In this context, the ABF suit the treatment of mixed UASB blackwater effluents and greywater attributing to the retention of biosolids in the filter matrix and preventing the sludge from toxic shocks under high organic loadings.

2.7 High-rate anaerobic bioreactors and its configurations

One of the crucial achievements in the development of anaerobic wastewater treatment was the introduction of high-rate reactors in which retention of biomass and waste liquid were separated from each other (Lettinga, Rebac & Zeeman 2001). The term “high-rate” refers to anaerobic treatment systems meeting at least the following two conditions (Lettinga, De Man

& Hulshoff 1987): (1) High retention of viable sludge under high loading conditions and (2) Proper contact between incoming wastewater and retained sludge. In the high-rate systems such as UASB and ABF, wastewater flows through the anaerobic sludge where it undergoes biodegradation, and organic matters are converted into biogas and sludge. Due to higher retention of sludge and proper mixing between the incoming wastewater and sludge, high rate bioreactors provide a high reaction rate per unit volume thus reducing the reactor volume which enables the application of high volumetric loading rates (Rebac et al. 1999) and low energy requirements (Rajeshwari et al. 2000). Some of the essential features of high-rate bioreactors are summarised in **Table 2.7**.

Table 2.7: Characteristics of different reactor types (Alptekin 2008).

Reactor type	Start-up period (months)	Channelling effect	Effluent cycle	Gas solid separation device	Carrier packing	Typical loading rates (kg COD/m^3.d)	HRT (d)
CSTR	-	NP	NR	NR	NE	0.25 - 3	10 - 60
Contact	-	NEx	NR	NR	NE	0.25 - 4	12 - 15
UASB	4 - 16	Low	NR	Essential	NE	10 - 30	0.5 - 7
ABF	3 - 4	High	NR	Beneficial	Essential	1 - 40	0.5 - 12
AFFFEB	3 - 4	Less	R	NR	Essential	1 - 50	0.2 - 5
AFB	3 - 4	NEx	R	Beneficial	Essential	1 - 100	0.2 - 5

CSTR: Continuous stirred tank reactors; AFFFEB: Anaerobic fixed-film fluidised expanded bed; AFB: Anaerobic fluidised bed; NP=Not present; NR=Not required; R= Required, NE=Not essential, NEx=Not existent

Use of the high-rate bioreactors provides excellent opportunities for the treatment of low-strength wastewaters due to excellent retention of biomass and decoupling of HRT and SRT while overcoming the design-related problems such as unstable operation in the conventional anaerobic treatment systems (Yu & Anderson 1996). For instance, UASB, packed-bed (fixed-film) and fluidised-bed reactor retain active biomass within the bioreactors. Furthermore, the application of high-rate reactors upheld the status that anaerobic digestion is a cost-effective and efficient technology to realise its environmental protection (Parawira et al. 2004). To provide options in achieving the cost-effectiveness and efficiency of the high-rate reactors, the essential developments in the configurations of anaerobic bioreactors are explored.

To achieve the better efficiency of the reactor through the decoupling of HRT and SRT, the different anaerobic reactor designs are configured. Based on the comparison of additional reactors types and configurations, the reactor choices and working process of the reactor designs are provided in **Table 2.8**. The recent development in the anaerobic configuration had been the application of anaerobic down-flow fluidization at laboratory scale with good performance (Escudié et al. 2011). On the other hand, the improved reactor configuration can reduce space instability, such as compartmentalised anaerobic reactor (CAR). The CAR comprises a distribution zone, a reaction zone, and a separation zone by adding three inners, which appears to keep the stability of space (Ji et al. 2012). However, its application in the treatment of domestic wastewater is unclear. Amongst the reactor configurations, the UASB is widely used for the treatment of sewage due to the formation of dense biomass called sludge granules forming the sludge bed and blanket at the bottom of the reactor due to its up-flow hydraulic and organic loadings. It is important to note that these characteristics of sludge granules sludge is not observed with any other anaerobic bioreactor configurations.

Table 2.8: Common anaerobic reactor configurations (Sattler 2014).

Type	Biomass	Working process	HRT (hrs)	COD treated (mg/L)	OLR (kg COD/m^3/day)	CODtotal (%)
Anaerobic biofilter (ABF)/ Packed Bed Reactor (PBR)	Attached	Biomass is grown on a media-supported biofilm. It is possible to maintain a long SRT (on the order of 100 days).	24-48	20,000	1-6	< 90
Expanded bed reactor		Microbes stick themselves to tiny media like sand. The up-flow of feed causes the media to extend.			4.4	89
Fluidized bed reactor (FBR)		Tiny media, such as sand or granulated activated carbon, are used to bind microbes. The up-flow of feed causes the media to extend.	3-100	5,000	10-20	> 90
Anaerobic contact (AC)	Suspended	A biomass-settling continuous stir tank reactor (CSTR) with an external tank. To sustain a long SRT, settled biomass is recycled.	12-120	5000	1-8	90
Sequencing batch reactor (SBR)		In one tank, all phases of wastewater treatment (filling, reacting, sedimentation, and decanting) are completed in order.	6-12		1.2-2.4	75-98
Up-flow sludge blanket reactor (UASB)		The formation of dense biomass called granules is aided by hydraulic and organic loading conditions, resulting in a sludge blanket at the reactor's bottom.	4-8	15,000	12-20	90-95
Membrane bioreactor (MBR)		Uses membrane to aid solids/liquid separation. Long SRTs regardless of HRT.	12-360		2-22	

2.8 Up-flow Anaerobic Sludge Blanket Reactor

Due to higher removal efficiency of organics unlike in aerobic systems, the preference of anaerobic treatment of wastewater as an alternative wastewater treatment was embodied, leading to the development of UASB reactor (Lettinga 1995). Lettinga and his group developed the UASB reactor at the University of Wageningen in the Netherlands. Initially, the UASB reactors were developed in the 1970s for the treatment of highly concentrated sugar industrial wastewater at mesophilic temperatures (Sandino 2004). After intensive investigation of different industrial wastewater accruing to its benefit of the UASB system such as reduction of sludge and production of biogas led to the application of the UASB reactor concept in the treatment of municipal wastewater.

The accompanying concepts are considered into the process design of the UASB to meet the basic requirements for a high-rate anaerobic wastewater treatment system (van Haandel, Catunda & Lettinga 1996). Under the hydro-dynamic mechanisms of the up-flow hydraulic regime of wastewater, well-settleable and flocculent or granular type of anaerobic sludges are developed and formed in the sludge bed located in the bottom of the reactor. The influent is uniformly spread over the sludge bed bottom and follows an upward path to the level of the effluent collection at the top of the reactor. As the substrates in the influent wastewater passes through the sludge bed and encountering contacts with the biomass, due to the biological processes the diffusion occurs between the biomass and the substrates results into biogas in the form of methane gas (CH_4). The rising biogas bubbles and the influent wastewater with kinetic energy enable the mixing between the influent organic material (nutrients) and the bacteria (methanogenic) in the sludge. The rising sludge gets settled back to the sludge bed in the reactor by installing a deflector and a gas-liquid-solid-separator (GLSS) to separate the three phases in the reactor: gas (biogas); liquid (the effluent); and solid (the sludge) at the top part of the UASB reactor.

The essential characteristic of UASB is the development of sludge granules, where the developed granules carry the robust features of overcoming disturbances in the treatment system (Mungray, Murthy & Tirpude 2010). The robustness of the UASB is indicated by the replacement of primary settler, the anaerobic sludge digester, the aerobic step (activated sludge, trickling filter, etc.) and the secondary settler in a conventional aerobic treatment plant (Latif et al. 2011); however, effluents from the UASB reactors usually need further treatment. Due to the high treatment capacity of high-rate reactors compared to expansive low-rate centralised treatment systems enables the provisions to use compact and economic WTTPs such as UASB reactor system under the scheme of decentralised household treatment system. However, a start-up in UASB is a time-consuming step in the treatment of wastewater.

2.8.1 Start-up of UASB reactor treating domestic wastewater

The start-up is the period of immobilization of sludge in the UASB reactor. Due to the slow growth rate of anaerobic microbes, particularly the methanogens and slow adaptation of the biomass to the characteristics of the wastewater to be treated in the reactor, the start-up period is time-consuming. However, the complex domestic wastewater differs from other types of wastewaters since the domestic wastewater contains bacterial populations necessary for the anaerobic digestion. Surprisingly, the anaerobic treatment of domestic sewage can be started without the need for inoculation since domestic sewage contains the bacterial cells (Doku 2002). Studies are conducted on the anaerobic treatment of dilute municipal wastewater without inoculum and achieved the average removal of organics and nutrients (Álvarez et al. 2006). For instance, the start-up of a UASB plant treating domestic raw sewage ($T > 20°C$) was achieved under HRT of 6 hours within 6 - 12 weeks (Lettinga et al. 1993).

Since the start-up is a time-consuming process, to reduce the time duration often, the anaerobic reactors are seeded with suitable inoculum in most of the studies investigated. The start-up can be accelerated, while adding cationic polymer of 80 mg/L in the lab-scale reactor, the solids with more massive than 0.5 mm began to form granules around day 50 and at the same time, the granulation took place in the control reactor for around 70 days (Show et al. 2004). Although the start-up of anaerobic reactors depends on parameters such as organic loading rates (OLRs) and sludge loading rates (SLRs), the resulting quality development of granular sludge in UASB sludge bed can take higher loading rates with a very short period to achieve steady-state again (Ghangrekar et al. 1996).

2.8.2 Steady-state behaviour in the UASB Reactor

The sludge mass begins to accumulate in the reactor after the start-up period of the UASB reactor. A steady-state of the reactor is established when organic matter present in the wastewater does not gather in the treatment system (Doku 2002) indicated by the steady removal of COD. When this state is attained, the daily mass of influent COD is equal to the sum of the daily mass of COD leaving the system and the methane in the excess sludge in the effluent gets oxidized (Van Haandel & Lettinga 1994).

2.8.3 Biogas production

The anaerobic digestion is only the current biological process which can produce biogas – a mixture of methane (CH_4) and carbon dioxide (CO_2) (Náthia-Neves et al. 2018). Instead of composting, in the absence of oxygen under anaerobic digestion, the organics in wastewaters are biodegraded into useful biogas, and the end digestates are used as fertilizers after proper treatment. Also, the high organic loads are reduced into a smaller volume of sludges controlling the removal of septages without polluting the environment.

Biogas from sewage digesters contains about 65 - 80% *v*/*v* methane, and the remaining consists of carbon dioxide, nitrogen, water vapour and a small fraction of hydrogen sulphide (Speece 1983). A substantial portion of the biogas produced remains dissolved in the liquid phase (mainly CO_2) and leaves the system in the effluent. The loss could be between 20 - 50% of the produced biogas (Van Haandel & Lettinga 1994). An increase in the gas production rates was attributed due to the periodic removal of 50% of the sludge (Seghezzo et al. 1998). The production of biogas indicated the overall reactor performance; however, the stress status of the reactor is not shown (Boe et al. 2010). Still, for the production of biogas, research and development had been directed to the retention of high active microorganisms for rapid and effective treatment (Goswami et al. 2016). The retention of microorganisms led to the development of microbial sludge bed formation in UASB. That is why the UASB is widely used in the treatment of municipal wastewater.

2.8.4 UASB treatment of municipal wastewater

Lab-scale UASB studies were carried out in early 1976 to treat low-strength wastewater (Lettinga, Roersma & Grin 1983). Raw domestic sewage (140 - 1100 mg/L COD) were treated at ambient temperature (8 - 20°C) using UASB and obtained a removal efficiency of 50 - 65% for an influent COD (< 300 mg/L) and achieved an efficiency of 65 - 90% more significant COD (> 400 mg/L) (Lettinga 1980). Thus, the concept of UASB appeared quite attractive for the treatment of raw domestic sewage due to its simplicity, compactness and low cost (Lettinga, Roersma & Grin 1983).

In the recent developments, different reactors configurations are employed to treat low-strength wastewater such as municipal wastewater. The UASB and ABF processes have been modified to use the best features of each to treat wastewater (Cakir 2004). A combination of UASB and ABF reactor concepts is merged, forming a hybrid reactor where the packing media is placed in the top of the UASB (Elmitwalli 1999). On the other hand, the expanded granular sludge bed (EGSB) reactors employ recycling of wastewater/sludge from the reactor to improve the wastewater/sludge contact. To accommodate an upward recycle flow (4 - 10 m/h), EGSB reactors are designed with a higher height/diameter ratio as compared to UASB reactors (Seghezzo et al. 1998). Other anaerobic processes such as anaerobic expanded/fluidised-bed (Jewell 1981) and anaerobic sequencing reactor (Ndon & Dague 1997) are also used for the treatment of low-strength wastewater. However, the UASB reactors were developed for effective domestic wastewater treatment (Rizvi et al. 2015).

In large-scale UASB reactors, De Man and Campos in 1986 were the first to demonstrate low-strength wastewater treatment (Cakir 2004). The highest COD removal efficiency obtained was 74% where 1200 m^3 UASB reactor used to treat municipal wastewater in Kanpur, India (Draaijer et al. 1992). The same removal efficiency of 74% was obtained, when investigated a full-scale study on sewage discharged from a low-income community in Sumare, Brazil (Vieira et al. 1994). Using a partitioned UASB reactor, evaluated the domestic sewage treatment from small villages in Brazil with a removal efficiency of 79% at an HRT of 7.5 h (Chernicharo & dos Reis Cardoso 1999).

A number of studies over the years have indicated that anaerobic processes in the UASB reactor can successfully handle urban wastewater as shown in **Table 2.9**:

Table 2.9: Studies of urban wastewater treatment using up-flow sludge blanket (UASB) reactors (Sattler 2014).

Authors (year) and Region	Design of reactor	Scale of reactor	Wastewater (COD mg/L)	Temp. (°C)	HRT (hrs)	OLR (kg COD/m^3/day)	Removal efficiency (%)				
							BOD	COD	TSS	N	Gas prod. (m^3/m^3/day)
Kato (1994) Brazil	UASB	Lab	Synthetic (422 - 943)	30	2 - 29	0.3 - 6.8	-	86 - 95		-	-
Lettinga (1996) Netherlands	UASB or EGSB	Lab	Pre-settled (<1000)	15 - 20		-	-	65 - 84		-	-
Bandara (2012) Japan	UASB	Lab	Raw (173 - 211)	6 - 31	2 - 8	-	-	50 - 71 (sum-mer)		-	< 0.1
Yu (1997) Singapore	UASB	Pilot	-		5 - 6	-	65 - 80	55 - 75	67 - 81		-
Gallagher (2010) USA	UASB	Pilot (95 L)	Blackwater	17 - 28	55 - 86	0.23 - 0.45		72	95	-34 (TN) -58 (NH_3)	-
Cardinali (2013) Brazil	UASB	Pilot (16.8 m^3)	Pre-settled	25	8 - 10	0.8 - 1.2 (rainy season) 1.2 - 1.6 (dry season)	-4 to 46%	50 - 63	59 - 73	-27 to -32	0.09 - 0.24
Oliveira and von Sperling (2008) Brazil	UASB	19 full-scale WWTP	Different				72	59	67	-13% (TN)	-

2.8.4.1 Modified UASB for the wastewater treatment

To overcome and improve the performance of the conventional UASB reactors such as improper mixing and contacts of sludge with wastewater, the UASB reactors were modified to enhance mixing and contacts. De Man in 1988 was the first to use expanded granular sludge blanket (EGSB) reactor to treat low-strength wastewater obtaining a removal efficiency of 20 - 60% soluble COD (Cakir 2004). While modifying the UASB reactor to achieve better performance, the most crucial feature of UASB reactors was the imposed upward flow of in-fluent which forces proper contact between active biomass and wastewater (Nnaji 2014).

Other investigations on the modified UASB reactors are shown in **Table 2.10**.

Table 2.10: Studies using Modified UASB reactors on domestic wastewater treatment (Cakir 2004).

Authors (year) and Region	Reactor design	Reactor scale	Wastewater (COD) mg/L	Temp. (°C)	HRT (hrs)	OLR (kg COD/m^3/day)	Removal efficiency (%)
							COD
De Man (1988) Netherlands	EGSB	LP	Low strength wastewater (150 - 600)	12-20	2 - 3		20 - 60
Van der Last & Lettinga (1992) Netherlands	EGSB	F	Domestic sewage (391)	16-19	1.5 - 5.8	2.7 - 9.4	30
Bogte (1993) Netherlands	UASB-septic tank	D	Domestic wastewater (821)	12.9	57.2	0.34	3.8
Bogte (1993) Netherlands	UASB-septic tank	D	Domestic wastewater (976)	13.8	44.3	0.53	33
Bogte (1993) Netherlands	UASB-septic tank	D	Domestic wastewater (1716)	11.7	202.5	0.20	60
Wang (1994) Netherlands	HUSB	LP	Sewage (650)	15.8	3	5.2	37 - 38
Yu (1997) Britain	ABR	L	Municipal wastewater (338 - 516)	18-28	2 - 16		67.8 - 83.5

HUSB: Hydrolytic up-flow sludge blanket; LP: large pilot, F: full scale, D: demonstration, L: large

2.8.5 Other types of reactors to municipal wastewater treatment

Besides the use of high-rate anaerobic treatment systems, other types of treatment systems are also used to treat municipal wastewater. The pilot-scale Up-flow Septic Tank (UST) in the treatment of residential wastewater showed promising results with the removal of 85%, 77%, and 86% of BOD, COD and TSS respectively under a 24 h HRT at steady state (Moussavi, Kazembeigi & Farzadkia 2010). This on-site treatment system appears additional improvement to the conventional horizontal septic tanks used at the household level. Two innovative Modified Septic Tank (MST) systems comprising attached and suspended growth indicated a slight improvement in the system performance over the suspended growth system (Abbassi et al. 2018). On the other hand, organic removal efficiencies were low in the MST and high in the anaerobic hybrid (AH) reactor (Sousa & Chernicharo 2006).

There are other treatment reactors, which are used to treat the municipal wastewater as given in **Table 2.11**:

Table 2.11: Other types of reactors for treating municipal wastewater are being researched (Sattler 2014).

Authors (year) and region	Reactor design	Reactor scale	Wastewater (COD) mg/L	Temp. (°C)	HRT (hrs)	OLR (kg COD/m^3/day)	Removal efficiency (%)				
							BOD	COD	TSS	N	Gas prod. (m^3/m^3/day)
Bodik (2002) Slovak	SBR	Lab	Raw & Synthetic (500 - 860)	9 - 23	6 - 46		48 - 96	56 - 88	75 - 92		
Metcalf (2009) USA	Aerobic activated sludge		Pre-settled				80 - 95	80 - 85	80 - 90		
Cubas (2011) Brazil	SBR	Lab (5 L)	Synthetic (521 - 557)	30	8			87			
Chunjuan (2011) China	EGSB	Lab (18 L)	Raw	13 - 25	0.4 - 3.4	2.6 - 38.1		61 - 93			
Prieto (2013) USA	MBR	Lab	Synthetic	37	72			98		95.5	0.45
Zhang (2013) China	MBR	Lab	Synthetic (375.8 - 411.3)			1.08		90		73 (TN), 97 (NH_4-N)	

SBR: Sequencing batch reactor; EGSB: Expanded granular sludge blanket; MBR: Membrane bioreactor

2.8.6 Constraints of UASB applications in wastewater treatment

The performance of UASB may become less efficient for sewage containing high amounts of non-settleable suspended solids (Bal & Dhagat 2001). The UASB effluents are satisfactory with 60 - 75% BOD_5 removal rates, but UASB reactors cannot produce a quality effluent by itself (Chernicharo et al. 2015). With minimum wastewater temperature over 18°C, UASB treatment followed by polishing steps is a treatment option increasingly implemented in warm weather countries such as Brazil (Sandino 2004). However, especially in developing countries with low-temperature conditions, pre-removal of particulate matter is a constraint to obtain quality effluents and biogas, which could hinder the widespread use of this anaerobic treatment technology (Chong et al. 2012). Studies show that the treatment of low strength wastewater under psychrophilic conditions are encouraging (Lettinga, Rebac & Zeeman 2001; Rebac et al. 1999).

Most of the troubles with anaerobic reactors are due to the lack of process control and improper operation management (Labatut & Gooch 2014). Therefore, researches are focused on improving the design and operation of UASB reactors. Specifically, scum accumulation, biogas and waste gas management, post-treatment and energy recovery, have received the most attention (Chernicharo et al. 2015). The other areas of research interests are highlighted in **Figure 2.2**.

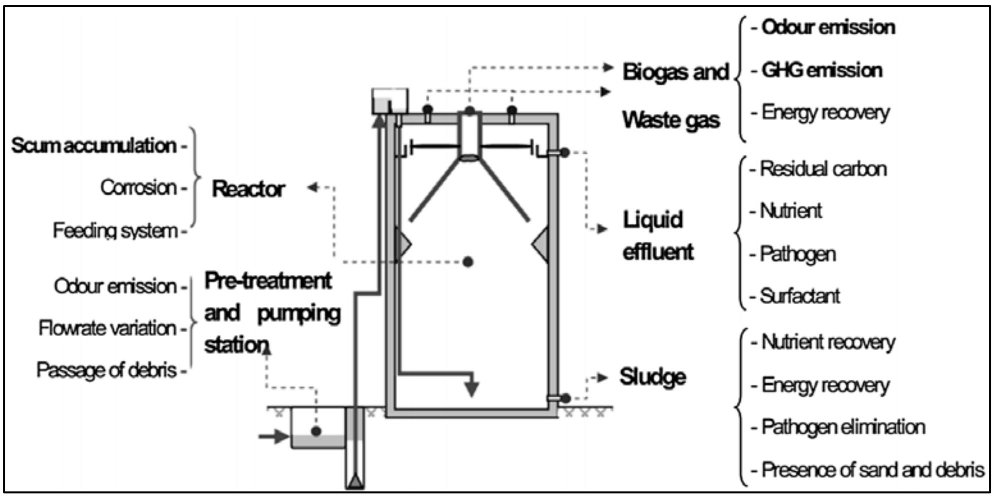

Figure 2.2: Areas of interest for improvements in UASB reactors (Chernicharo et al. 2015).

Besides the area of its interest, the high-rate UASB anaerobic sewage treatment systems are also constrained with its treatment system as addressed below (Chernicharo et al. 2015):

Constraints
• Adequate post-treatment or polishing steps are necessary to meet the discharge standards.
• CH_4 produced remains partially dissolved in the effluent as results of the influent COD concentration and the hydraulic flow. No measures are applied in full-scale to prevent CH_4 from escaping to the atmosphere.
• CH_4 collected is often not utilized for the generation of energy and not even flared, which contributes to greenhouse emissions.
• Limited experience with full-scale applications at moderate to low temperatures.
• Dissolved gases escape through effluents causing odour problems such as H_2S.
• High influent sulphate concentrations limit the applicability of sewage treatment due to odorous and corrosive nature of sulphide.

2.8.7 Post-treatment of municipal UASB effluents

High-rate anaerobic reactors can achieve high performance; however, their effluents rarely meet the institutional discharge standards in terms of nitrogen (N), phosphorous (P) and organic carbon (COD). With an influent COD of more than 250 mg/L, the post-treatment of UASB effluents are necessary before its discharge into the receiving water bodies (Ghangrekar & Kahalekar 2003). But the selection of post-treatment systems depend on the wastewater composition, performance of the anaerobic reactors, the purpose and regulation of discharge standards, also the operation and construction costs and importantly the flexibility and simplicity of the post-treatment technologies (Mai, Kunacheva & Stuckey 2018).

The recent development in the domestic wastewater treatment involves anaerobic treatment while emphasizing the post-treatment of its effluent (von Sperling & de Lemos Chernicharo 2002). For the post-treatment of UASB effluents, the ABF as one of the processes that provides the best treatment performance (Mai, Kunacheva & Stuckey 2018; Oliveira & Von Sperling 2009). On the contrary, the ABF had the worst average COD removal efficiency, unless the process is aimed to produce methane, the anaerobic process is not recommended for the post-treatment of anaerobic reactor effluents (Mai, Kunacheva & Stuckey 2018). In this study, the ABF as the secondary treatment of mixed UASB blackwater effluents and greywater generated steady production of biogas which supported that ABF as a suitable process for the post-treatment of UASB effluents.

Under the tropical conditions, the methanogenesis in two-step treatment system seems to occur in the first step; therefore, importance is emphasized to study a two-step system consisting of UASB followed by removal of suspended solids in the second step (Leitão et al. 2006). For the post-treatment of UASB effluents, use of downflow hanging sponge (DHS) appears to be attractive due to the presence of excellent sites for the growth and attachment of active biomass in the sponge media (Uemura & Harada 2010). Usually, aerobic treatment is used to supplement the post-treatment of anaerobic effluents. However, there could be instances in which the association of different anaerobic processes might meet less restrictive requirements such as efficiency and final effluent concentration (Chernicharo 2006). In this study, while investigating the UASB+ABF combined system met the discharge requirements under the local ambient conditions in Bhutan.

The secondary treatment units are employed to alleviate the hydraulically overloaded UASB reactors as the primary units due to which the effluents from UASB do not comply with the environmental standards. This is because under the anaerobic conditions, the components of the organic matters are minimally affected by the anaerobic treatment namely nutrients (N & P) and pathogens (viruses, bacteria, protozoans, and helminths). Post-treatment of UASB effluents are necessary for achieving the strict environmental discharge standards; however, there are no consistent practises related to this vital stage of post-treatment at the international experience (Chernicharo & Machado 1998). In particular, no reports are available on practices and experiences with the post-treatment of municipal wastewater in Bhutan even the primary treatment.

The results of several post-UASB municipal wastewater treatment studies are presented in **Table 2.12**:

Table 2.12: UASB studies on municipal wastewater post-treatment (Sattler 2014).

Authors and Region	Reactor design	Reactor scale	Wastewater (COD) mg/L	Temp. (°C)	HRT (hrs)	OLR (kg COD/m^3/day)	Removal efficiency (%)				
							BOD	COD	TSS	N	Gas prod. (m^3/m^3/day)
Yu (1996) Singapore	Baffled: UASB, fixed-film, UASB-ABF	Lab (33.6 L chambers)	Pre-settled (368 - 516)	17 - 28	4 - 10	0.92 - 2.43		68 -84	-35 to 35	-30 to -40 (NH_4^+)	0.09 - 0.30
Aiyuk (2004) Belgium	Chemically enhanced primary treatment, UASB, zeolite for NH_4^+ removal	Lab (2.1 L UASB)	Raw (522 - 822)	33	10, 5	0.4 - 0.7	85	91	88	99 (TKN)	
Salazar-Pelaez (2011) Mexico	UASB+ultrafiltration membrane	Lab (700 L UASB)	Raw (738 - 1191)	25 (assumed)	4,8,12			86	> 95		< 0.1
Alvarez (2008) Spain	2-stage: UASB, UASB	Pilot (25.5 m^3, 20.4 m^3)	Raw (118 - 381)	14 - 21	5-6	S1:2.8 - 5.7 S2:6.5 - 13.9	0.5 - 3.2	50-77	49 - 65	76 - 89	
Almeida (2009) Brazil	UASB/trickling filter	Pilot (22.1 m^3 &16.8 m^3)	Pre-settled (303 - 403)	20 - 25	7.7, 8.5	0.46 - 0.71	70 - 80	65-67	74 - 67		
Chernicharo (2011) Brazil	UASB/trickling filter	Pilot (22.1 m^3 &16.8 m^3)	Pre-settled		8	1.2, 0.8	55 - 70	30-44	75		
Oliveira and von Sperling (2008,2009) Brazil	UASB+post treatment	8 Full-scale plants	Raw	Different			88	77	82		
Chernicharo (2009) Brazil	Preliminary screening, UASB, trickling filter, secondary settling	Full-scale (2212 m^3 and 605 m^3)	Pre-settled				72	59	67	-13% (TN)	

S1: Stage 1, S2: Stage 2

2.8.8 Appraisal of UASB for the wastewater treatment

The reluctance to install anaerobic systems is due to the presumed insecurity, low acceptance of loading rates, slow recovery after failure and specific requirements of the waste composition. However, these presumptions have been proven otherwise, especially for the high-rate reactors like UASB, and now the commercial interest in anaerobic treatment is increasing rapidly (Bal & Dhagat 2001). The critical limiting factor for maintenance and retention of biomass in high-rate reactors is the slow growth of methanogens. High biomass content in the reactor is essential while operating with very dilute waste strength to achieve better conversion efficiency. Notably, the methanogens attach themselves readily to surfaces of the carriers media or other bacterial communities in the anaerobic treatment systems (Bal & Dhagat 2001). This remarkable characteristic has made it possible to develop high-rate UASB reactors as known today.

The UASB reactor is one of the reactor types, which accommodates loading capacity, and mainly it differs from other reactors by its simplicity in design. The UASB process is a combination of physical and biological process (Bal & Dhagat 2001). In the physical process, solids and gases are separated from the liquid, while in the biological process, the organic matter is degraded under anaerobic digestion. No separate settler with sludge return pump is required as in the anaerobic contact (AC) process. Also, there is no loss of reactor volume through filters or carrier materials as in the case with the anaerobic biofilters (ABFs) and other fixed-film types. There is no need for high rate recirculation and consequential pumping energy as in the case with the fluidised-bed reactor. Within the range of high-rate treatment systems, the UASB provides more excellent alternative supported with a robust and straightforward system without mechanized parts and elimination of installation complexity valued with minimal operational costs (Stazi & Tomei 2018). The UASB require less working volume with a reduced footprint which features higher biogas production handling higher COD loading rates and achieve adequate treatment due to presence of granular or flocculent sludge bed (Mao et al. 2015). So far, the inclination to form sludge granules have been observed with anaerobic microbes only, which is not the case with aerobic biomass (Narayanan & Narayan 2019).

Operating a UASB reactor at maximum sludge retention capacity improve its methanogenic potential and the also the SS entrapment capacity since the sludge-bed is maintained in its full volume and height. The excess sludge leaving with the effluent is held in another treatment unit to enhance the treatment capacity of the system such as in ABFs where the escaped biosolids are entrapped and retained in between the filters preventing loss of sludge solids from the treatment system. Surprisingly, the sludge solids rising from the sludge-bed in the UASB have settling properties to settle back into the sludge blanket and then into the sludge bed and finally consolidating its entrapment capacity. This entrapment and settling of biosolids are further ensured by the placement of deflector first and second with a settler, namely gas-liquid-solid-separator (GLSS) placed above the deflector at the apex of the UASB reactor. Through this appraisal, the UASB reactor treatment configuration seems to meet the underlying concept of efficient and straightforward biological degradation of sewage (Foresti 2001). Innovative approaches to UASB treatment include the use of UASB treatment for nitrogen removal as well as for hydrogen and volatile fatty acid production, while an increased full-scale application of UASB technology is needed to achieve circular economy and sustainability with the prospect of efficient biogas exploitation meeting renewable energy targets and reduction in green-house gases emission (Mainardis, Buttazzoni & Goi 2020). The treatment capacity of UASB is complimented through the improved ability of anaerobic biofilters reviewed in the literature.

2.9 Anaerobic biofilters

The initial anaerobic biofilters were developed by (Young & McCarty 1969) consists of plexiglass columns with 140 mm in diameter and 1.83 m in height with a total volume of 28.5 L as shown in **Figure 2.3**. The filter comprises smooth quartzite stones with 25 - 38 mm diameter having a porosity of about 42%. The treatment of protein-carbohydrate wastewater (1500 - 6000 mg/L COD) was studied with HRT of 4.5 - 72 h, at an organic loading rate (OLR) of 0.96 - 3.40 kg COD/m^3.d of the filter volume and temperature of 25°C with a COD removal efficiency of 68.4 - 98.6% (Young & McCarty 1969).

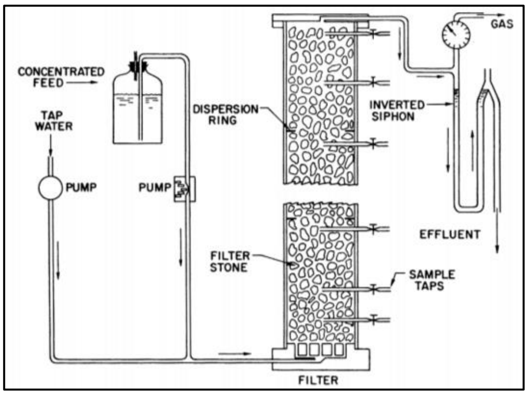

Figure 2.3: The plexiglass column used as an anaerobic biofilter (Source: Young & McCarty 1969).

This experiment added an element of stability and reliability of the anaerobic biofilters, which was missing in conventional anaerobic treatment. Further, anaerobic biofilters benefited the post-treatment option for septic tank effluents due to low operation and maintenance costs, simplicity of operation and low production of sludge (de Oliveira Cruz et al. 2019) and even serving the urban population larger than 50,000 inhabitants (Chernicharo 2006). Most of the anaerobic biofilters are operated under the up-flow mode of operation to achieve the robust hydraulic regime in the treatment system.

2.9.1 Types of up-flow anaerobic biofilters

Depending on the design of filters and operation conditions, up-flow anaerobic biofilters are of three different types: (1) Fully-packed reactor: filled with the filter materials; (2) Modular reactor: filled with the particular filter materials; (3) Hybrid reactor: operated with a sludge blanket at the bottom zone and filter material forming a filter on the top zone (Melik 2007). The support filters include a variety of natural materials such as smooth quartzite pebbles, shells, granite stones, cinder, brick ballast and synthetic materials like polyvinyl chloride sheets, needle-punched polyester, glass, raschig rings and other materials.

Maxham and Wakamiya first developed the anaerobic hybrid (AH) reactor in 1981 (Melik 2007). The performance of AH reactor is influenced by contact of the wastewater with both the suspended growth in the sludge layer and the attached biofilm in the matrix of filter materials. However, when the performance of ABF reactor is compared to AH reactor, ABFs provided a better total COD removal due to higher removal of suspended COD achieved (Elmitwalli et al. 2002a). As an advantage of the AH reactor, the excess sludge from the hybrid reactor was more stabilized with a higher settling capacity and dewaterability. The better removal of COD achieved in ABF than AH reactor could due to the greater depth of construction in ABF where the entrapment of suspended solids is attained more through the development of anaerobic biofilm than that of AH reactor.

2.9.2 The process of anaerobic biofilm development

The anaerobic biofilter (ABF) is primarily a contact process where the substrates in wastewater flow over the fixed biomass growth on the media contained in the bioreactor (Yu, Zhao & Tang 2006). The retention of biomass in the filters is achieved by immobilizing microorganism either as an attached biofilm on the surface of the support materials or by process of aggregation of bacteria in suspension between the filters (Jawed & Tare 2000). The immobilisation of microorganisms is influenced by the cell-to-cell interaction or by the environmental composition, notably the main characteristics of the biofilter materials: form, size, porosity, specific surface, stable quality and its electrical charges (Fia et al. 2010). The prime role of the filter materials is to hold biomass either as a biofilm attached to the surface of the filter material or as retain as loose solids suspended within matrices of the filters (Elmitwalli et al. 2000). The performance of these biofilter materials are directly related to the ease with which microbes can become attached or entrapped; primarily, the state of the surface of the biofilter material is crucial (Manariotis & Grigoropoulos 2006b).

In the anaerobic biofilter, about 60% of the biomass is the sludge accumulated in the pores of filter material (Manariotis, Grigoropoulos & Hung 2010). In this context, most of the organic matter removal is accomplished by the presence of micro-organisms in this portion of the biomass. Otherwise, the biomass in the system is attached in the form of a thin film layer on the filter material. Therefore, the soluble organic compounds in the inflowing wastewater get diffused to the surface of the biomass through kinetics; thereby, the organics are converted into methane and carbon dioxide. The merit of ABFs are that the granulated microorganisms are retained in between the medium, but also the biomass adhere on the media; thus, the hybridization of retained microbial floc and attached biomass are created (Goswami et al. 2016). The biofilter medium in the ABF also acts as a gas-solid-separator which helps to provide uniform flow through the reactor, improves the contact between the substrates and the biomass, and facilities the accumulated biomass in the medium to generate long SRT (Yu, Zhao & Tang 2006).

The theory and kinetics of the anaerobic biofilter process were examined by several investigators when employing Monod kinetics and the other first-order kinetics; both indicated an adequate performance of the anaerobic biofilter (Cakir 2004).In particular, the ABFs are used and recommended for dilute soluble wastes which can be made dilute by recirculation of effluents (Jawed & Tare 2000). Therefore, the use of ABFs for dilute soluble wastes implies that the low-strength wastewater such as domestic sewage is applicable for ABF treatment.

2.9.3 Applications of the anaerobic biofilter in domestic/municipal wastewater treatment

The anaerobic treatment is widely used in other wastewaters: food processing (slaughterhouse), vegetable tanning, and industrial wastes (pharmaceutical, tannery, and brewery). Since not much treatment are identified in the domestic/municipal wastewater treatment, the examination the anaerobic biofilter treatment seems a promising method for the treatment of raw municipal wastewater (Manariotis & Grigoropoulos 2006b) . Most of the anaerobic biofilter treatment of domestic sewage is based on lab-scale treatment. Due to comprehensive lab-scale studies made on it, the list of studies is not enumerated here, which could also indicate the maturity of the biofilters studies. While at the pilot-scale treatment, the use of anaerobic biofilters was limited. Initial reports were made on the use of a pilot-scale anaerobic biofilter for the treatment of municipal wastewater (Genung et al. 1980). Containing 25 mm ceramic raschig rings with a total reactor height of 5.6 m and 1.5 m in diameter, mostly the system was operated for two years under an ambient wastewater temperature ranging from 10 - 25°C. The filter achieved an average overall removal efficiency of BOD_5 removal 55% and 75% for total suspended solids (Genung et al. 1980). However, the large full-scale application of anaerobic biofilter treatment on domestic/municipal wastewater is limited through the literature search in this study. Thus, in this context, it appears that the use of anaerobic biofilter treatment suits the decentralised on-site sanitation in the developing countries.

2.9.4 Trends in the anaerobic biofilter treatment of wastewater

Coulter first developed the anaerobic biofilter treatment in 1957 (Cakir 2004). As a part of the development, an up-flow packed column known as "Up-flow Anaerobic Biofilter" with rock-packed media for the treatment of various industrial wastewaters were used. The performance of ABFs has been investigated on a variety of sewage in order of ascending year of study (Kaetzl 2019): food processing wastes, brewery wastes, wheat starch-gluten plant waste, pharmaceutical wastes, landfill leachates and high strength acid wastewater, shellfish processing wastes, heavy metals, and removal of organic particulates. Most of these investigations were directed at the treatment of medium to high strength wastes (1000 mg COD/L or more significant) considering the types of wastes to be treated (Kaetzl 2019). Further, application of biofilters indicated a great potential in greywater treatment and its reuse (Jung et al. 2019). It appears investigations on anaerobic biofilter treatment of domestic wastewater are the recent waste types to be treated in ABFs in context to the developing countries.

In the treatment of domestic wastewater by ABF, a removal of COD up to 90% was achieved (Bodik, Herdova & Drtil 2000a). To achieve similar COD removal rates with a hydraulic loading rate (HLR) of 0.05 $m.h^{-1}$ and a wastewater production between 100 - 300 lpcd, ABF would need a footprint of 0.08 - 0.25 m^2/person (Kaetzl 2019), which in turn is significantly less space than pond systems (1.2 - 5.0 m^2/person/d) or constructed wetlands (3.0 - 5.0

m^2/person/d) (Von Sperling & de Lemos Chernicharo 2005). These records indicate the suitability of ABF on-site treatment in the urban small plot sizes in Bhutan, where urban space is limited.

2.9.5 Enhanced performance in anaerobic biofilters

The biofilm developed on the media or the carriers has the potential to deter the impact of low temperature on the embedded biomass; therefore, the suspended filling or fixed carriers/media is a standard treatment system under low temperature (Zhou et al. 2018b). In the recent development and application of membrane bioreactors (MBRs) in the existing municipal WWTPs have improved the performance of municipal/domestic wastewater treatment during winter or low temperature due to the presence of microporous membrane for solid/liquid separation (Zhou et al. 2018b).

In the modified septic tank (MST) system comprising both anaerobic and aerobic chambers operated as two systems, the corrugated plastic fixed-growth media showed a slight improvement in system performance over the suspended growth (Abbassi et al. 2018). The attached-growth technologies (AGTs) were projected as an alternative to the conventional wastewater treatment process and septic tanks (Loupasaki & Diamadopoulos 2013). During the bio-film treatment process of high synthetic wastewater, the treatment performance appeared to improve by modifying the surface of the high-density polyethylene (HDPE) media using sandpaper (Almomani, Örmeci & Kiely 2019).

The two-stage system (modified septic tank - anaerobic biofilter) comprising two chambers (modified septic tank & anaerobic biofilter with baked clay media) delivered effluent quality with high resilience to hydraulic shock loads indicated the feasible option of on-site domestic wastewater treatment for the settlements in unsewered rural and peri-urban areas in India (Sharma, Khursheed & Kazmi 2014). The implementation of a treatment unit to retain the excess sludge in the anaerobic biofilter improved the robustness of the overall treatment system. Also, the presence of fixed-media in the anaerobic biofilter reduced the effluent variations due to the natural events of sludge expulsion as well as the sludge washout due to imposition of hydraulic or organic loads (Sharma, Khursheed & Kazmi 2014). This low-cost enhanced treatment by the anaerobic biofilter befits the improved on-site sanitation in the unsewered households of Bhutan.

2.9.5.1 Modified anaerobic biofilters

To provide improved performance, the anaerobic biofilters are modified to incorporate the increased surface area and porosity. For the first time, Guiot and Van den Berg in 1982 used plastic rings as packing media above the UASB reactor (Cakir 2004). The hybrid anaerobic biofilters containing reticulated polyurethane (RPU) were used to treat domestic wastewater (Elmitwalli 1999; Elmitwalli 2000). A variety of studies on modified anaerobic biofilters are shown in **Table 2.13**:

Table 2.13: Studies on the treatment of municipal wastewater with a modified anaerobic biofilter (Cakir 2004).

Authors (year) & Region	Reactor design (packing material)	Reactor scale	Wastewater (COD mg/L)	Temp (°C)	HRT (hrs)	OLR (kg COD/m^3/day)	Removal efficiency (%) COD
Miyahara & Noike (1994)	Hybrid up-flow anaerobic biofilter (vinylidene chloride looped fibre)	Lab	Synthetic wastewater (550)	20	24	0.55	75
Elmitwalli (1999) Netherlands	ABF+Anaerobic hybrid reactor (reticulated polyure-thane foam sheets)	Lab	*Raw sewage (456) *Pre-settled sewage (339 & 403)	13	8	-	*66 *61
Hutnan (1999) Slovakia	Anaerobic hybrid reactor (tubular plastic carrier)	Lab	Synthetic wastewater (6000)	37	0.4 - 12 days	0.5 - 15	80 - 90
Wu (2000) Singapore	Anaerobic hybrid reactor (raschig rings)	Lab	Synthetic wastewater (5000)	35	5 - 60	0.5 - 15	71 - 98
Elmitwalli (2000) Egypt	ABF+Anaerobic hybrid reactor (verti-cal sheets of RPF)	Pilot	Raw domestic sewage (772)	13	*4 + 8 *2 + 4 *3 + 6	-	*70.9 *58.6 *63

2.9.6 Trends in the development of local anaerobic biofilters

The most common filter materials used in ABFs are rocks or plastic support materials. However, due to high transportation or production costs of these materials, use of ABFs on a broader scale could be a challenge, particularly in the developing countries (Frankin 2001). Studies have been investigated on the use of different low-cost fillers for ABF using locally available materials. For instance, with woodchips as a filter material for ABF, a mean BOD removal rate of 78 - 83% is reported (Viraraghavan, Landine & Pyke 1989). At the same time, waste tyre ABF achieved 60% COD removal from domestic wastewater (Reyes et al. 1999). With bamboo rings, a mean COD removal between 60-80% is obtained (Camargo & Nour 2001). Using local burnt brickbats in ABFs indicated consistent performance and high treatment efficiency at lower HRTs without clogging of media during the treatment of municipal wastewater (Bodkhe 2008). The low-cost volcanic rocks such as Tezontle as local media in Mexico were used as a packing medium. They achieved an organic matter removal efficiency above 80% under HRT of 24 h at 35°C (López-López et al. 2013). Such as the use of coconut shells in ABF achieved a COD removal of 65 - 73% treating domestic wastewater (de Oliveira Cruz et al. 2013). Agave fibre as aerobic biofilter fillings removed 62 - 80% from pre-settled domestic wastewater (Vigueras-Cortés et al. 2013). The locally available material Cocopeats in Vietnam were used as biofilter packing medium removed 98.9% BOD under simulated septic tank wastes subjected to aerobic, anoxic and anaerobic treatment in the bioreactor columns (Thomson 2014). Anaerobic biofilters comprising biochars were superior or equal to woodchips and gravel filters when investigated for the removal of COD, TOC and turbidity (Kaetzl et al. 2018). The use of non-woven fabric in the bioreactors showed the positive effect of nutrient removal from raw sewage in a household sewage supply (Chmielowski et al. 2019). Proving an efficient way for direct treatment of sewage is the reuse of polyurethane foam (PUF) in the form of trims of upholstery foams in a system comprising septic/storage tank and a vertical flow biofilter (Dacewicz 2019a). The use of local coconuts husks in ABFs demonstrated the treatment of sewage in small communities which is currently considered as solid waste (de Oliveira Cruz et al. 2019). The comprehensive list of local biofilters are reported in the study (Kaetzl 2019). Local products tend to be ideal for the treatment of domestic wastewater. Yet plastic wastes, industrial wastes, and organic materials are not evaluated as filter materials for the domestic wastewater treatment in Bhutan.

However, in recent years, a number of filter studies have shown that anaerobic biofilters can successfully handle municipal wastewater, as shown in **Table 2.14:**

Table 2.14: The use of anaerobic biofilters (ABF) to treat municipal wastewater has been studied (Sattler 2014).

Authors (year) and Region	Reactor design (packing material)	Reactor scale (volume)	Wastewater (COD mg/L)	Temp. (°C)	HRT (h)	OLR (kg COD/m^3/day)	Removal efficiency (%)				
							BOD	COD	SS	N	Gas prod. (m^3/m^3/day)
Bodik (2002) Slovak Rep.	Up-flow ABF (plastic insulating tubes)	Lab	Raw (100 - 200) & synthetic	9 - 23	6 - 46	1 - 6	41-96	46-92	72 - 95		
Garbossa (2005) Brazil	Anaerobic/aerobic filter (polyurethane foam cubes/porous stones)	Lab	Raw	19 - 20	5 - 15			84		96 (TKN)	
Manariotis (2006a) Greece	ABF (ceramic saddles/smooth plastic rings/crushed stones)	Lab (12.5 L)	Raw	25.4	24	0.12 - 1.82		74-79	95 - 96		
Saddoud (2007) Tunisia	ABF (UF membrane)	Lab	Raw	37	15	0.2 - 2	88	90 (soluble)	100		
Wasik (2017) Poland	Downflow ABF (PET flakes)	Lab	Pre-treated sewage (360.70)		1.8 - 56 days		50-80			66.74 (NH_4-N)	
Melidis (2009) Greece	ABF (porous glass rings)	Pilot	Raw	25 - 35	5.5 - 8.6	1.7 - 2.8		52	57	21 (TKN)	0.10 - 0.51
Oliveira and von Sperling (2008) Brazil	Septic+ABF	19 full-scale WWTP	various	Different			59	51	66	24	

2.9.6.1 Effect of filter materials as biofilter medium in ABF

The filter material constitutes the significant capital cost of the treatment system. Since the anaerobic biofilter is a hybrid system comprising both attached and entrapped biomass; therefore, the choice of filling material is essential (Switzenbaum 1983). Different filter materials have been tested as support material for the retention of biomass in the ABF system (Kaetzl et al. 2020). The support material with a high surface roughness activated the development of biofilm than smooth support material (Gourari & Ackkari-Begdouri 1997). Laboratory results in the different studies suggest that texture of the filter material and porosity play a significant role in the performance of up-flow anaerobic biofilters. This indicates that to optimize the retention of biofilm attached on the surface of the filter material and entrapment of suspended biomass within the interstitial void spaces, the support material with open-pored surfaces and high porosity is of utmost use. Study on biomass growth on the pieces of polyvinyl chloride (PVC) plastic etched glass and baked clay showed that support material remarkably influenced the rate of attachment and growth of bacteria converting acetic acid to methane (Show et al. 2004). Most of the studies show that the retention of biomass in the filters is a significant factor for satisfactory performance of COD removal.

Using reactive material in the on-site system has been tested and found to be an effective and appropriate technology for the under-resourced regions (Oladoja 2017) such as tropical clay materials with gravel pebbles. The use of polyethene terephthalate (PET) and polypropylene (PP) in the aerobic fixed-bed reactors (ABFR) led the growth of biofilm (Lapo 2018). Local broken brick-bed wetlands provided better removal of nutrients (NH_4^+, NO_3^-, PO_4^{3-}) and better adsorption sites from hospital wastewater in constructed wetlands (Guerrero et al. 2009). The use of a crushed lava rock filter for greywater treatment at the HH level demonstrated the potential to reduce the greywater pollutants in urban slums (Katukiza et al. 2012). The coconut shells were used for the treatment of domestic raw sewage having high resistance to biological degradation as filling materials (de Oliveira Cruz et al. 2013). The use of coconuts husks in anaerobic biofilters improved the performance of the sand filter and final effluent quality treating the domestic wastewater in small communities instead of treating as solid wastes (de Oliveira Cruz et al. 2019). Due to the high porosity of Aqwise carrier media (ABC5), the treatment efficiency was slightly better than the system having baked clay media (Sharma & Kazmi 2015a). However, the clay media showed better performances in terms of minimizing the effect of variable hydraulic shock loadings during the non-steady flow conditions (Sharma & Kazmi

2015a). Use of filter material such as biochar from Miscanthus grass in the anaerobic biofilters appeared better removal of faecal indicator bacteria and COD removal compared to the slow sand filters (Kaetzl et al. 2020). The reuse of shredded PET bottles and fragmented polyurethane foam (PUF) sponge waste as a filling of vertical-flow filter (VFF) proved to be an effective method in the treatment of wastewater effluents from a septic tank (Dacewicz & Chmielowski 2019b). These indicate the better performance of the locally available materials as low-cost biofilter media in ABFs.

2.9.7 Appraisal of ABFs

This attached-growth system such as ABFs can treat wastewater at the local level with excellent tolerance to the variation in hydraulic and pollutant workloads while having its effluent to be used for local irrigation under the pretext of integrating into the local landscape while having low foot-print with low operation and maintenance cost (Loupasaki & Diamadopoulos 2013). The bio-film reactors can recover swiftly after an unfed period, besides the benefits of simple construction, elimination of mechanical mixing, better stability of higher loading rates, and capability to withstand large toxic and organic shock loads (Lettinga 1995).

However, the biofilm reactors are challenged with the increase in the size of reactor volume due to its active volume occupied by the media compared to other reactors. Also, another pertinent constraint is the clogging of the reactor due to increased thickness of biofilm and high suspended solids concentration in the wastewater (Rajeshwari et al. 2000). Nevertheless, under the anaerobic conditions, solid productions are low and the ability of the anaerobic biofilters to store such solids for a more extended period is an added beneficial feature of this anaerobic biofilter process (Dahab 1982). The features of ABF with the local biofilters as biofilter medium suit the alternative treatment options such as UASB+ABF combined system under the context of inadequate on-site sanitation in Bhutan.

2.10 UASB+ABF two-staged anaerobic treatment systems

Domestic wastewater generally contains more particulates than soluble. In the presence of particulates/suspended solids (SS), the rate-limiting step (hydrolysis) of the anaerobic digestion process become too slow at low temperature, leading to accumulation of undegraded SS in the reactor's sludge bed (Seghezzo 2004). Under these conditions, the SRT in the reactor may become too short to provide adequate treatment efficiency and satisfactory sludge stabilisation at a reasonable HRT (Seghezzo 2004). Therefore, effluents from the UASB contain considerable SS due to discharge of sludge particles from the reactor due to the hydrodynamic mechanisms in the reactor. To suit the effluents from the UASB to the discharge standards, the up-flow anaerobic biofilters (UABFs) appear to complement the removal of UASB effluents (Chernicharo & Machado 1998). This is because the long SRT can be achieved in UABFs for the digestion and organic conversions due to the presence of its fixed-filter package arrangements in the reactor.

The association of UASB and ABF seemed to be the most suitable for the anaerobic treatment of domestic wastewater in the developing countries (Alptekin 2008). The wastewater treatment systems using UASB reactors followed by ABFs represented a simple flow sheet. This simplicity of the flow in the reactor systems is due to the stabilisation of sludge bed in the primary treatment unit of the UASB reactor and the secondary treatment of ABF. This merging of stabilised anaerobic processes between the two anaerobic systems complemented to the reduction of power and operational costs of the treatment plant (Chernicharo 2006). This was indicated by use of pilot and demonstration-scale ABFs with local blast furnace slag as a local biofilter for the post-treatment of anaerobic effluents from septic tanks and UASB reactors which removed 80 - 95% under varying HRT of 1.5 - 24 hours (Chernicharo & Machado 1998).

On the contrary, in context to the ABF+UASB staged treatment system, the performance of the second stage could be improved by enhancing the removal of solids using ABF as a first stage instead of the UASB reactor. The ABF reactor with the filter media of reticulated polyurethane foam (RPF) sheets showed an average CODss removal efficiency of 71% under an HRT of 4.6 h at 25°C (Halalsheh 2002). While combined (ABF+UASB) reactors operated at (4+8) hours respectively seemed to have an average CODt removal efficiency between 70 - 82% during both summer and wintertime (Halalsheh 2002). Improvements in the treatment performance systems were due to the satisfactory removal of influent suspended solids in the first stage ABF, which is suitable for the operation in the second stage UASB (Sawajneh, Al-Omari & Halalsheh 2010). However, disadvantage using ABF as the first stage treatment would be clogging of filters due to the accumulated suspended solids present in the blackwater. Thus, UASB suits as the first stage or the primary treatment unit of domestic sewage.

With two-staged (UASB+UASB) reactors with (8+6) hours HRTs, resulted in average CODtot and CODss removal efficiencies of 51% and 60% (Halalsheh 2002). The second stage had a poor performance due to heavy scum formation, and sludge washout influenced the performance of the second stage reactor. With (23+12) hours HRT in two-staged (UASB+ABF) reactors using reticulated polyurethane foam (RPF), it resulted in CODt and CODss removal efficiency of 67% and 82% (Alrajoula, Halalsheh & Fayyad 2009). The improved performance of the second stage is due to the entrapment of suspended solids in the RPF inside the reactor. In two-staged (UASB+ABF) reactors, with (15+4) hours HRT resulted in CODt and CODss removal efficiency of 55% and 65% using RPF as biofilter medium (Halalsheh, Abu Rumman & Field 2010). The second stage performed well in removing the volatile fatty acids (VFA) due to better biological degradation and methanization taking place inside the RPF in the reactor. These studies indicate the UASB reactor treatment and use of suitable biofilter media in the ABF reactor can complement the performance of the two-stage (UASB+ABF) treatment system. This is because anaerobic pre-treatment does not enable the production of hydrogen rather pH is controlled in the separate reactor making anaerobic digestion process faster, yet for combined pre-treatment, their synergistic effect not only improves biogas yield but also reduces the formation of inhibitive and recalcitrant components (Atelge et al. 2020).

Recent developments indicate two-stage process technically improves the biomethane productivity by upto 30% when compared to single-stage process (Rajendran et al. 2020). Although the concept of two-stage reactor was designed for the high-solid substrates such as agricultural residues; however, it is used in wastewater treatment systems as well. Considering the better performance of the two stage anaerobic digestion research carried out so far, it is anticipated the research will continue to expand further which could technically advance processes in the future with sustainable success (Rajendran et al. 2020).

The performance of various two-staged anaerobic treatment systems for performance and operation conditions are enumerated, as shown in **Table 2.15**:

Table 2.15: Performance and operation conditions for two-staged anaerobic systems (Halalsheh 2010).

1st stage						2nd stage			COD_{tot} removal efficiency (%)		
Sl. No.	System	T (°C)	HRT (hr)	V_{up} (m/h)	OLR (kg COD/m^3.d)	HRT (hr)	V_{up} (m/h)	OLR (kg COD/m^3.d)	1st stage	2nd stage	Total system
(1)	$HUSB^+$ + UASB	9-21	3	1.00	5.2	2	--	--	37-38	27-48	51-69
(2)	UASB + UASB	9-26	6.1	0.60	1.1-1.5	4	0.9	1.0-1.7	--	--	40-60
(3)	UASB + UASB	23	6.4	0.62	0.8	5.6	0.7	0.2	83	36.1	89
(4)	$HUSB^+$ + UASB	21-22	2.8	2.50	2.4	6.5	0.94	0.7	35	44	64
(5)	UASB + UASB	26	8-10	0.50-0.65	3.6-5.0	5-6	0.76-0.94	2.9-4.6	53	4	55
(6)	UASB + ABF	23	23	0.21	1.4	4	0.5	3.7	50	35	67
(7)	UASB + ABF	24	16	0.20	2.6	4	0.5	3.7	32	35	55
(8)	This study UASB + ABF	15-30*	24	0.04	0.10**	8.8	0.23	0.22***	64	54	65

+Hydrolytic up-flow sludge bed.
* Ambient room temperature.
**Based on soluble COD.
***based on soluble COD: UASB blackwater effluent (20%) & greywater (80%) *v/v*

The configuration of the reactor is significant as it influences the ease of sludge settling and available of film surface area. However, the UASB reactors and ABFs can accumulate more active biomass than other reactors and can operate well with dilute wastes such as domestic wastewater at higher loading rates (Bal & Dhagat 2001). The hybrid UASB achieved better removal efficiencies than the conventional UASB due to the better granulation of sludge and establishment of biofilm in the ABF (Loganath & Mazumder 2018). This establishment indicated UASB reactors could be successfully combined with ABF to reduce the washout of biomass, preventing the need for an additional unit (Dutta, Davies & Ikumi 2018). The various combination of UASB reactor with post-treatment units are given in **Table 2.16**.

Table 2.16: Removal efficiency of UASB reactor with post-treatment (Mungray 2010).

UASB + post-treatment	Parameters						
	BOD (%)	COD (%)	TSS (%)	NH_3 (%)	TN (%)	TP (%)	FC (log units)
UASB+FPU	47	28	41.3	-13	50 - 65	> 50	3 - 5
UASB+SPP	88.5	-	46	-	-	-	5.7
UASB+OFP	71.4	50	66.7	35-65	< 65	< 35	2 - 3
UASB+SAF	52.4	44.3	66.7	50-85	< 60	< 35	1 - 2
UASB+TF	68.5	57.1	68.8	50-85	< 60	< 35	1 - 2
UASB+ABF	46.6	30	36.7	< 50	< 60	< 35	1 - 2
UASB+DAF	83 - 93	83 - 90	90 - 97	< 30	< 30	75 - 88	1 - 2
UASB+CW	90.4	85.9	94.7	-	-	-	-
UASB+ASP	98.8	97.5	95.3	50 - 85	< 60	< 35	1 - 2
In this study UASB+ABF	73	65	74	< 30	< 60	< 35	1 - 2

FPU: final polishing unit, SPP: shallow polishing ponds, OFP: overland flow process, SAF: submerged aerated filter, TF: trickling filter, ABF: anaerobic biofilter, DAF: dissolved air floatation, CW: constructed wetlands, ASP: activated sludge process

2.11 Concluding remarks

This chapter presented an overall view of concerning wastewater issues, and inadequate treatment in the developing world and context to the scope of alternative improved wastewater sanitation in Bhutan under the purview of the anaerobic treatment system. The anaerobic treatment system includes the general theory of anaerobic digestion, anaerobic digester technology, anaerobic digestion of sewage and research into the UASB and ABF. UASB, ABF and modified reactors have demonstrated excellent performance for high and medium strength wastewater. With the emergence of high-rate bioreactors such as UASB and ABF, two-step/two-stage anaerobic treatment system has developed to reduce the organic pollutants from discharging into the environment using the biofilters as the biofilter medium in the ABF reactor. Considering the physical and biological treatment systems, the local biofilters are suitable in providing cleaner on-site wastewater technology and to reduce localised pollution workloads. There are a few significant examples of real anaerobic domestic wastewater treatment in different parts of the world, happening mostly in the developing countries with tropical to moderate climates. There are no records on the use of the UASB and ABF treatment of real domestic wastewater in Bhutan using local biofilters under the local ambient conditions. Most studies were performed at the laboratory lab scale than that of full-scale application. Therefore, demonstration of pilot-scale treatment of domestic wastewaters is required to develop an application of UASB and ABF technology that may be adequately designed for operation and maintenance at a house hold level under the scheme of decentralised treatment system.

The previous studies show success with anaerobic treatment under ambient temperature. Still, as far the author is concerned there are no studies carried especially for anaerobic biofilters in Bhutan at the pilot and lab-scale. This review were performed to evaluate the anaerobic treatment for future adoption at a larger household level, mainly in the unsewered areas and the rural areas at large.

CHAPTER 3

WASTEWATER MANAGEMENT IN URBAN BHUTAN: ASSESSING THE CURRENT PRACTICES AND CHALLENGES

*This Chapter was published in Process Safety and Environmental Protection (2019)

Dorji, U., Tenzin, U.M., Dorji, P., Wangchuk, U., Tshering, G., Dorji, C., Shon, H., Nyarko, K.B., Phuntsho, S. 'Wastewater management in urban Bhutan: assessing the current practices and challenges', *Process Safety and Environmental Protection*, 132 (2019) 82 - 93

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CHAPTER 4

EXPLORING SHREDDED WASTE PET BOTTLES AS A BIOFILTER MEDIA FOR IMPROVED ON-SITE SANITATION

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Dorji, U., Tenzin, U.M., Dorji, P., Pathak, N.K., Johir, M.A.H., Volpin, F., Dorji, C., Chernicharo, C.A.L., Tijing, L., Shon, H., Phuntsho, S. 'Exploring shredded waste PET bottles as a biofilter media for improved on-site sanitation', *Process Safety and Environmental Protection*, 148 (2021) 370 - 381

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CHAPTER 5

ON-SITE DOMESTIC WASTEWATER TREATMENT SYSTEM USING SHREDDED WASTE PLASTIC BOTTLES AS BIOFILTER MEDIA: PILOT OPERATION IN BHUTAN

*This Chapter has been submitted for review in the *Process Safety & Environmental Protection* (2020).

U. Dorji, K. Norbu, P. Dorji, U. Badetia, C. Dorji, H.K. Shon, S.Phuntsho, 'On-site domestic wastewater treatment system using shredded waste plastic bottles as biofilter media: pilot operation in Bhutan', To be reviewed in *Process Safety & Environmental Protection* (2020).

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CHAPTER 6

LOCALLY AVAILABLE MATERIALS AS A BIOFILTER FOR THE SECONDARY TREATMENT OF UASB EFFLUENT AND GREYWATER

*This Chapter will be submitted for review in *Journal in Engineering Management* (2020).

U. Dorji, K. Norbu, P. Dorji, U. Badetia, C. Dorji, H.K. Shon, S.Phuntsho, 'Industrial slags, waste plastic strips and local bamboos as a bio-filter for the secondary treatment of UASB effluent and greywater', To be reviewed in *Journal in Engineering Management* (2020).

6.1 Introduction

On-site sanitation is an issue to be addressed essentiallly in developing countries due to the lack of municipal sewer connections. Concerning the rapid urbanisation and with the unplanned growth of infrastructures, the HHs are not permitted to dispose of greywater to surface water drains. In the absence of sewerage system, greywater is either discharged into the septic tanks thereby inundating the septic tanks or it is mostly being directly disposed to surface water drains without any treatment. In either of the cases results in environmental pollution. Settlements without sewer connections to wastewater treatment plants rely on on-site treatment: community toilets, composting toilets, and on-site sanitation: aqua privies, soak-pits, pit latrines and other on-site systems (Sharma & Kazmi 2021). At present, some core town areas in Bhutan are connected to public sewerage services. However, many urban settlements lack sewer connections, especially at the periphery of urban centres, predominantly relying on conventional "septic tanks". Existing on-site treatment systems such as "septic tanks" are often inadequate due to poor design, construction and operational issues (Van Haandel et al. 2006). Due to the resulting low treatment efficiency of mismanaged "septic tanks", their wide-scale use significantly contributes to environmental pollution (Sharma & Kazmi 2021).

Wastewater treatment plants (WWTPs) in Bhutan are centralised and publicly funded. Constructing wastewater treatment plants is expensive while there are practical challenges to providing sewer connections to all households in Bhutan's hilly landscape. In the rough terrain of Bhutan, spaces are limited to accommodate "septic tanks" due to rapid and unplanned growth of infrastructures. Based on the on-site building survey and analysis of urban plots, we found that urban plots are often too small to accommodate the construction of soak-pits following the national regulations; therefore, treatment of septic tank effluent is omitted (Dorji et al. 2019). Therefore, there is an anticipated demand for WWTPs with small footprints; such as anaerobic treatment as an alternative to existing "septic tanks" for on-site treatment to serve the majority of the urban population (80%) who are currently without public sewerage system (Dorji et al. 2019).

Anaerobic treatment of domestic wastewater is an attractive treatment option for small communities (Bodík, Herdová & Drtil 2002), considering the resource and urban space constraints in the developing countries. Sewage treatment by primary sedimentation followed by activated sludge treatment is very efficient, but comes with high capital and running costs which does not offer a sustainable solution for the developing countries (El-Khateeba et al. 2018). Low-cost treatment with low energy requirements is the key to sustainable waste management (Zeeman & Lettinga 1999). Thus, UASB as a low-cost and low energy technology has been widely adopted for domestic wastewater treatment in the tropical and sub-tropical developing countries limited by financial constraints (Camargo & Nour 2001; Seghezzo 2004). However, UASB effluents do not meet most national discharge limits but require further treatment to enable safe discharges. For the post-treatment of UASB effluents, commercial filters are commonly used but are expensive. Thus, to realise the benefits of UASB as an affordable compact technology, low-cost post-treatment options have been investigated by several researchers (El-Khateeb et al. 2009; Khan et al. 2016).

To improve the performance of post-treatment of UASB effluents, various packing materials have been tested in anaerobic biofilters to increase the surface area for attached growth of biomass. The basic concept of biofilters is to provide a surface area to which bacterial communities can attach, which facilitates the microbial growth (Wąsik & Chmielowski 2017). The nature of the biofilter media in the ABFs must enable retention of biosolids for degradation of dissolved organic loads (Shawaqfah 2014). Several types of low-cost packing materials have been studied for their effectiveness in post-treatment of anaerobic effluents (Kaetzl et al. 2018).

Compared to conventional media (quartz sand, gravel, clay, rock), plastic fillings are light-weight, have a large surface area and less tendency to clog (Wąsik & Chmielowski 2017). In a vertical flow filter consisting of mechanically shredded polyethylene terephthalate (PET) bottles and polyurethane foam (PUF) wastes, domestic sewage in Poland was treated and achieved COD removal between 28 - 89% (Chmielowski et al. 2018). About 20 - 22 tonnes of waste plastics bottles are collected every month in the capital Thimphu City of Bhutan (NEC 2016a). For various reasons, there is still no plastic recycling industry in Bhutan and limited reuse of waste plastic bottles. At the same time, existing "landfills" are overwhelmed with municipal wastes and often have leachate problems since many of the landfills in Bhutan are not designed and thus lacking leachate management issues. Besides the use of plastic shreds in the earlier studies, one option is to use these waste plastic bottles as biofilter media in the form of strips and bundles for the anaerobic biofilter treatment of domestic wastewater since plastics have a long life span suited for use in wastewater treatment.

Another alternative for a low-cost packing material is the availability of local bamboo, which grows in Bhutan. Whole and half ring slices have been used in Brazil for sewage treatment resulting in COD removal of 60 - 80%, while whole bamboo ring slices facilitated better biofilm development (Camargo & Nour 2001). Even with low porosity and specific surface area, bamboo biofilters used in an anaerobic biofilter for treatment of slaughterhouse wastewater achieved 95% and 75% COD removal under HRTs of 7.5 days and 2 days respectively (Tritt et al. 2017). A carrier anaerobic baffled reactor (CABR) using bamboo was used for decentralised domestic sewage treatment in rural China resulting in COD removal ranging between 69 - 79% under HRT of 18 - 48 h (Feng et al. 2008). Studies have also shown organic support media, such as charcoal, facilitated nutrient removal due to the development of biofilm on the macropores (Karadag et al. 2015).

Slag filters have previously shown to achieve adequate removal of COD and improved production of biogas from livestock wastes using steel slags as an accelerant (Han et al. 2019). The most considerable amount of industrial waste, including iron and steel slags, are generated from the only industrial estate in Pasakha, which is significant for a small country like Bhutan (NEC 2016a). Proper management of iron and steel slags are critical due to limited space for dumping in Bhutan's predominantly 90% hilly terrain landscape. More importantly, under the strict national environmental regulations, steel slags cannot be disposed to landfill sites due to likely pollution of water bodies (Kuensel 2008). Also, due to improved behaviour of slags as strengthening of its granular base properties due to presence of lime and silica after the wastewater treatment, there is a potential application of iron and steel slags for use as construction materials such as alternative for aggregate in road construction instead of value material recovery (Zhang et al. 2020). To date, the use of slags in wastewater treatment has not been trialled in Bhutan.

This study aims to verify the suitability of shredded waste plastic bottles strips, semi-charred bamboo beads and industrial slags as low-cost biofilters for on-site secondary domestic wastewater treatment in urban areas of Bhutan, and investigate alternative packing arrangements, media and column sizes.

6.2 Material and Methods

6.2.1 General principles of the approach

This set of column studies was conducted in Bhutan, under different ambient conditions from the lac-scale research presented in Chapter 4 using plastic bottle shreds. Since the full-scale pilot presented in Chapter 5 had found significant fluctuations in the day-to-day composition of the residential wastewater (BW and GW), it was considered appropriate to use synthetic wastewater for the acclimatisation of the ABF microbes. A comparison could also be made of the relative performance of the different media and sizes under this stable feed.

Following the acclimatisation with synthetic wastewater, the media were then tested with actual domestic wastewater to assess their performance with varying HRTs, starting with the optimum HRT (12 h) observed from the synthetic influent. Shorter HRTs (8 h + 6h) were also checked since this would enable the construction of smaller treatment plants should this solution be adopted for real-life applications. For both the synthetic wastewater and the real wastewater, the different media were fed in parallel and therefore subject to the same ambient temperatures. Similarly, the different media were fed from a shared tank, and thus any fluctuations in influent composition would have affected all media columns.

6.2.2 Wastewater characteristics

The synthetic wastewater initially used in this study simulates blackwater generated from toilets and greywater from bathrooms and kitchens. Since the actual composition of wastewater in Bhutan is not available, the composition of the synthetic blackwater and greywater was the same as used for the lab-scale test on the plastic bottle chips (Kassab et al. 2013). All the chemicals used to replicate the carbon source, major nutrients (nitrogen and phosphorus) and micronutrients were of analytical grade (Sigma Aldrich, Australia). The wastewater characteristics of the synthetic influent, blackwater and greywater are provided in **Table 4.1**.

However, the lab-scale study using synthetic wastewater was also tested under the ambient conditions in Bhutan and compared to real sewage collected from the College residential buildings, as shown in **Table 6.1**.

Table 6.1: Average synthetic and real wastewater characteristics of mixed UASB blackwater effluent and greywater.

Parameter	Temp (°C)	COD_t (mg/L)	COD_s (mg/L)	TN (mg/L)	TKN (mg/L)	NH_4^+ (mg/L)	PO_4^{3-} (mg/L)
SWW	21 (±3.49)	429 (±39.12)	215 (±3.12)	51 (±3.09)	48 (±2.68)	20 (±1.01)	43 (±0.91)
DWW	26 (±0.81)	240.07 (±43.43)	77.77 (±19.95)	20.13 (±3.90)	17.52 (±3.96)	12.85 (±3.14)	4.42 (±0.78)

SWW: synthetic wastewater; DWW: real domestic wastewater
COD_t: total COD; COD_s: soluble/dissolved/filtered COD.
Values between brackets are standard deviations.

6.2.3 Selection of biofilter media

Although a large variety of designed synthetic filters are available in the international market, there is an absence of local materials specifically tested as filter media for the municipal/domestic wastewater industry in Bhutan. Based on the concept of value addition and reduction of non-biodegradable waste, materials including waste plastic bottles and industrial slags were selected for the research. Medium-sized bamboo was also chosen since it is locally available in parts of the country. Waste plastic bottles were manually shredded sliced into strips using an improvised shredding blade attached to a wooden block and roughened with sandpaper. The bamboo was charred using an open fire to facilitate the attached growth of biomass and chopped into 20 mm height (1/2, 1/4 & 1/8 bead). Industrial slags were collected from the backyard of the industrial steel plant and sieved using Indian Standard (IS) sieve sizes of 8 mm, 10 mm and 12.5 mm. A commercial filter media, Kaldness K1 filter media, was purchased from Allcare Ponds, Australia.

All biofilter media were weighed and counted before being placed in the ten ABF reactor columns. The packed columns were first filled with clear water to check for leaks and to rinse off any foreign substances on the surface of the biofilters. A free-board space under the column's flat lid was left for gas collection. The porosity/density of packed biofilter media was determined by measuring the volume of the water required to fill the bioreactor column of known media height to a specific height. Water is assumed to fill all the voids in and between the media. The details of the filter media are provided in **Table 6.2**.

Table 6.2: Slag, plastic, commercial and bamboo biofilter used and their essential characteristics.

Biofilter media types and their properties	**SF1**	**SF2**	**SF3**	**PF1**	**PF2**	**PF3**	**CF**	**BF1 (20 mm)**	**BF2 (20 mm)**	**BF3 (20 mm)**
Media size	8 mm	10 mm	12.5 mm	5000 mm x 3 mm	5000 mm x 5 mm	5000 mm x 7 mm	10.5 mm	1/8 bead	1/4 bead	1/2 bead
Thickness (mm)	-			~ 0.20 – 0.40			1	3		
Surface area per unit volume of packed media (m^2/m^3)	-			833.33	798.61	777.78	827.46	338.64	273.61	223.74
Packed media porosity (%)	45	49	51	77	80	82	68	37	48	59
Pore volume (L)	0.65	0.71	0.74	1.11	1.16	1.18	0.93	0.51	0.66	0.81
Numbers & weight (g)	1891 & 1150	882 & 1063	532 & 995	40 nos. & 345 g	23 nos. & 237 g	16 nos. & 209	1202 & 195	1005 & 541	406 & 436	166 & 357

SFs: slag filters; PFs: bundled waste plastic strips; BFs: semi-charred bamboo beads; CFs: commercial filters

6.2.4 ABF column system

The ten biofilter columns were made of transparent acrylic tubes (Plastix, Australia) with an internal diameter of 45 mm and a water column height of 1 m, as shown in **Figure 6.1**. Each column has a total volume of 1.59 L and an effective volume of 1.44 L. The effective volume of all the ten biofilters was packed with the biofilter media of different sizes as described in **Table 6.2.** All ten biofilters were connected as up-flow vertical bioreactors, aiming to enhance contact between biofilm and influent wastewater while preventing sludge loss from the columns. With each column, three sampling ports were placed at 300 mm c/c. Due to smaller sizes of columns, to keep the filter media intact, cuboidal marbles were placed at the top of the biofilter packing media to avoid the floating of the light shredded plastic. Wastewater was fed from the columns' lower side.

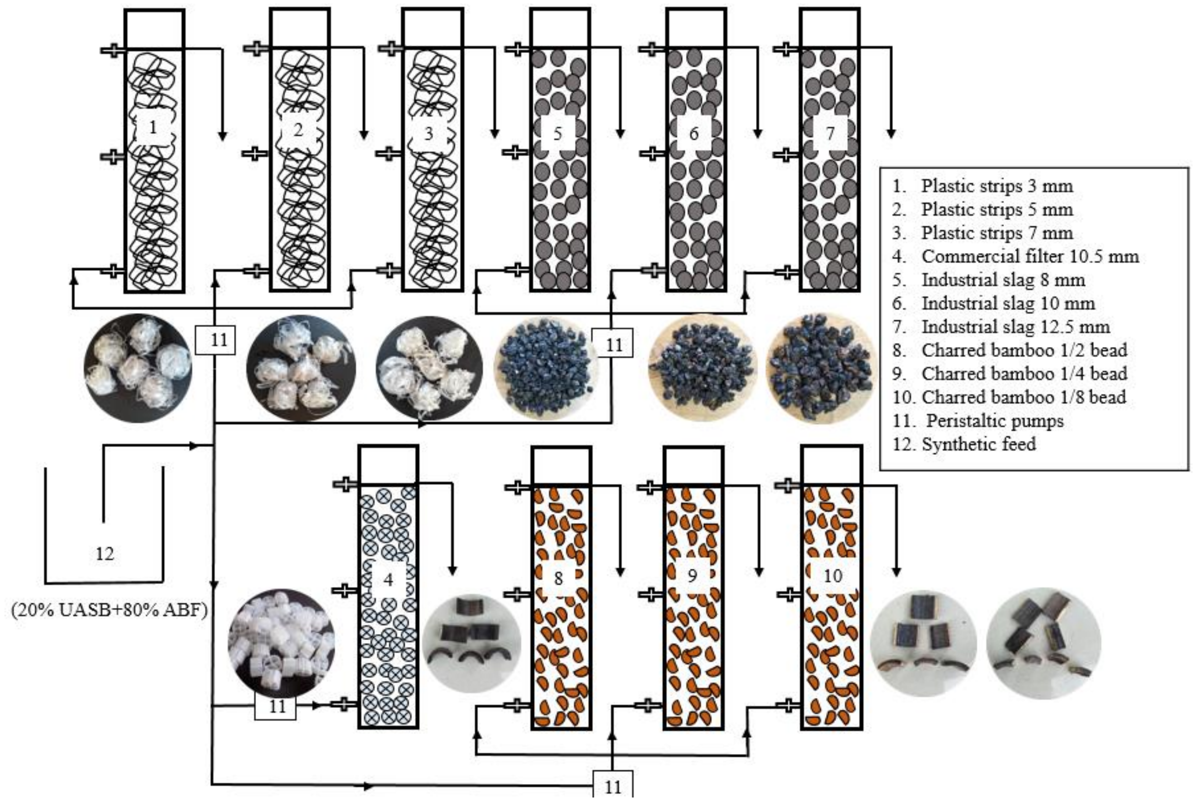


Figure 6.1: Schematic layout of the wastewater treatment system using anaerobic biofilter (post-treatment unit for combined UASB effluent and greywater).

6.2.5 Operation of the ABF columns for secondary treatment of domestic wastewater

The low-strength wastewater, such as domestic sewage does not produce enough biogas to warm up the treatment room for the bioreactors (Ho & Sung 2009). Even though anaerobic digestion is faster under higher temperature, the benefits of higher digestion rates are balanced by the cost of heating. Therefore, these lab study anaerobic biofilters were operated at ambient temperature in the pilot shed. The testing of the ABF columns was carried out in three phases: inoculation, acclimatisation and steady-state of continuous operation.

For the inoculation of the ABF columns, sludge was collected from the pilot UASB reactor, which had been under operation for seven months under ambient conditions (refer to **Chapter 5**). Since the sludge was thick and dense (TSS: 41,674 mg/L; VSS: 29,729; n=14), it was diluted by half with tap water to achieve a consistency which could be pumped into the ABF columns. About 50% of the pore volume of the media was filled with this diluted sludge and left unfed for 2-days to adapt and attain anaerobic conditions in the ABF columns. The length of this contact time/inoculation period was based on the first lab-scale study, which can vary from a few days up-to or more than one month. After the initial unfed period of 2-days, synthetic feed water was pumped into each column at a low concentration (COD not measured) and filled up to the empty-bed volume occupied by the media and again left unfed for 1-day. This was to enable adaptation of microbes to the synthetic feed water characteristics and also to prevent the washout of seed organisms. After this 1-day of the unfed period, synthetic wastewater was recirculated in all ten ABF columns under a 1 d-HRT to facilitate the development of biofilm. The inoculation was carried out for a month to ensure contact between biomass and substrates on the media in the columns. The organic mass fed into the ABF columns was as presented in **Table 4.1**. The pH in columns was maintained at 7 ± 0.5 with $NaHCO_3$ dosing in the feed water.

An HRT of 20 h appeared to result in optimal COD removal under anaerobic biofilter treatment of domestic wastewater in the lab-scale study with plastic bottles shred conducted earlier. After one month inoculation period, the ABF columns were operated at an HRT of 20 h continuously using the synthetic feed water replicating UASB blackwater effluent and greywater. The ten ABF columns were operated for seven weeks at a longer HRT of 20 h to acclimatise and achieve steady COD removal, as well as to prevent the accumulation of volatile fatty acids (VFAs) (Onwosi et al. 2019).

Then the HRT was gradually reduced to 12 h, 8 h and 6 h to avoid shock loading under operational conditions (refer to **Table 6.3**). The HRT in each of the ten ABF columns was calculated based on the measured pore volume of the media in the columns. The HRTs were reduced every 5 - 6 weeks, as the accumulated VFAs reduced under the anaerobic digestion process. The reduction in VFAs enabled the microbes to adapt to the increased OLRs in achieving steady-state organics removal.

Table 6.3: Operational conditions of the ABF columns system using synthetic wastewater.

Operational parameters	Operational conditions			
HRT (h)	20	12	8	6
OLR* (kg COD/m^3.d)	0.26	0.43	0.65	0.86
V_{up}+ (m/hr)	0.01	0.02	0.03	0.05

OLR*: Organic loading rate; V_{up}+: up-flow velocity

After 6 h HRT operation of ABF columns using synthetic wastewater for 150 days, real domestic wastewater of mixed UASB blackwater effluents and greywater (1:4 *v*/*v*) was introduced into the ABF columns at 12 h HRT (refer to **Table 6.4**). The 12 h HRT was chosen based on optimal effluent COD removal observed while using synthetic wastewater. It was presumed that after 150 days of operation using synthetic wastewater, the ABF columns should have fully stabilised their anaerobic conditions and be able to cope with the fluctuating loads of real domestic wastewater.

Table 6.4: Dimensions and operational conditions of the ABF columns system using real domestic wastewater.

Operational parameters	Operational conditions		
HRT (h)	12	8	6
OLR* (kg COD/m^3.d)	0.18	0.28	0.36
V_{up}+ (m/hr)	0.02	0.03	0.05

OLR*: Organic loading rate; V_{up}+: up-flow velocity

6.2.6 Wastewater sampling and analysis

Grab samples from the ABF columns were collected twice a week for monitoring water quality parameters, including pH, temperature, electrical conductivity (EC), turbidity (NTU) and oxidation-reduction potential (ORP). The grab samples were tested for COD every alternative week, as were nutrients (TN, Total Kjeldahl Nitrogen (TKN), NH_3-N, Total Phosphorous (PO_4^{3-}). As the total suspended solids (TSS) in the ABF columns from the effluent wastewater samples was insignificant, turbidity was measured instead. All wastewater samples were filtered through 0.45 μm Nylon filter (Agilent Made) before analysis. The COD, TKN and PO_4^{3-} were all assessed following Standard US Methods (APHA 1998). COD, PO_4^{3-}, TKN, NH_3-N and TVA were determined by the Closed Reflux Method using test kits (HACH, USA) and direct reading spectrophotometer (DR3900, HACH, USA). pH and ORP were measured using an ion-specific electrode probe for each parameter (Lab Quest, Vernier, USA). Temperature and electrical conductivity were measured using (HANNA Instruments, Australia) while turbidity was measured using a 2100P Turbidimeter (HACH, Australia). Biogas was collected from each column using 5 L gas sampler bags (Sigma-Aldrich, Australia), and its composition was measured using a Biogas Analyzer (BIOGAS 5000, Geotech, UK).

6.3 Results and Discussions

6.3.1 Start-up operation and steady-state of ABF column reactors

After inoculating the sludge for seven weeks, a steady-state is established, verified by steady COD removal under an HRT of 20 h (refer to **Figure 6.2**). The steady COD removal indicated that organic matter was not accumulating in the ABF columns. The start-up period can be considered complete and steady-state established once the effluent characteristics from the columns remained consistent under the influent organic loading. However, the break-up of carbon particles from the semi-charred surface of bamboo beads caused raised effluent COD from columns BF1 (1/8 bead), BF2 (1/4 bead ring) and BF3 (1/2 bead), but gradually reduced during operation (refer to **Figure 6.2**). The steady COD removal in the ABF columns was supported by managing the conducive operational conditions under prescribed limits of pH, as shown in **Table 6.5.**

Table 6.5: pH, ORP and effluent temperature in the ten column biofilters treating synthetic wastewater under decreasing HRTs.

<table>
<tr><td></td><td colspan="4">SFs</td><td colspan="4">PFs</td><td colspan="4">CF</td><td colspan="4">BFs</td></tr>
<tr><td>HRT (h) →</td><td>20</td><td>12</td><td>8</td><td>6</td><td>20</td><td>12</td><td>8</td><td>6</td><td>20</td><td>12</td><td>8</td><td>6</td><td>20</td><td>12</td><td>8</td><td>6</td></tr>
<tr><td>pH</td><td colspan="4">7.14 - 8.40</td><td colspan="4">6.90 - 7.65</td><td colspan="4">6.89 - 7.48</td><td colspan="4">6.53 - 7.24</td></tr>
<tr><td>ORP (- mV)</td><td colspan="4">(-) 314 – (-) 151</td><td colspan="4">(-) 332 – (-) 185</td><td colspan="4">(-) 308 – (-) 230</td><td colspan="4">(-) 314 – (-) 151</td></tr>
<tr><td>Effluent temperature (°C)</td><td colspan="4">16.2 - 27.6</td><td colspan="4">16.1 - 27.5</td><td colspan="4">16.2 - 27.5</td><td colspan="4">16.1 - 27.8</td></tr>
<tr><td>Room temperature (°C)</td><td colspan="16">16.7 - 27.6</td></tr>
</table>

When using the real domestic wastewater following the 150 days of operation with synthetic wastewater, steady-state of operation conditions were also attained, as shown in **Table 6.6**.

Table 6.6: pH, ORP and effluent temperature in the ten column biofilters using real domestic wastewater under decreasing HRTs.

	SFs			PFs			CF			BFs		
HRT (h) →	12	8	6	12	8	6	12	8	6	12	8	6
pH	6.62 - 7.42			6.52 - 7.23			6.52 - 7.07			6.56 - 7.35		
ORP (- mV)	(-) 214 – (-) 151			(-) 289 – (-) 173			(-) 286 – (-) 208			(-) 285 – (-) 167		
Effluent temperature (°C)	24.2 - 28.1			24.3 - 28.2			24 - 27.8			24 - 27.8		
Room temperature (°C)	24.3 - 28.3											

Start-up is considered to be complete when pH values settle within the optimum range (6.3 - 7.8) (Lay, Li & Noike 1998) for anaerobic digestion while attaining steady removal of COD. The variations of pH between the biofilters columns were kept within the prescribed limit by dosing the synthetic wastewater with sodium bicarbonate ($NaHCO_3$) based on the twice-weekly pH tests. When using real domestic sewage, the pHs naturally remained within the optimum range due to the regenerated alkalinity in the real wastewater (Lettinga & Van Haandel 1994).

For the process of biological nitrification and acidogenesis, optimum ORP is considered between -220 mV to -60 mV (Noike et al. 2004). Decreased HRT led to increase in ORP (without negative convention), pushing average ORP within the optimum range for the PF, CF and BFs, while ORP of SF was already within the accepted range. The numerical increase in effluent ORP following HRT reduction is attributed to the bacteria's increased oxidising ability (Fan et al. 2019). Though the decrease in HRT resulted in an incremental reduction in negative ORP value, it remained below -150 mV. However, an ORP of about -300 mV is generally taken to indicate full anaerobic conditions (Gerardi 2003).

6.3.2 Hydrolytic activity and acidifications in the ABF columns

Under consistent and steady wastewater pH, ORP and temperature, anaerobic digestion (Equation 6.1 - 6.4) in the ABF columns are facilitated by the production of volatile fatty acids (VFAs) measured as total volatile acids (TVA). VFAs are the leading indicator of an anaerobic digestion process and its instabilities (Ahring, Sandberg & Angelidaki 1995). The production of VFAs such as acetate, propionate and butyrate take place in a chemical reaction of glucose (Ososanya & Faniyi 2015) and anaerobic degradation of VFAs (acetate, propionate & butyrate) as shown in Equations 6.1 - 6.7 (Alimahmoodi & Mulligan 2008):

Hydrolysis: $(C_6H_{10}O_5)n + nH_2O \rightarrow nC_6 H_{12}O_6 + nH_2$……………………………(6.1)

Acidogenesis: $C_6H_{12}O_6 \rightarrow 3CH_3CH_2OH + 2CO_2$…………………………………(6.2)

Acetogenesis: $CH_3CH_2OH + 2H_2O \rightarrow CH_3COO^- + 3H_2 + H^+$…......………………...(6.3)

Methanogenesis: $CH_3COOH \rightarrow CH_4 + CO_2$...……………………………………..(6.4)

Glucose → 2 Pyruvate + 4 H (Emdden-Meyerhof-Parnas pathway)

2H producing reactions:

Pyruvate + H_2O → Acetate (C2) + CO_2 + 2H

$Acetate^- + H_2O \rightarrow HCO_3^- + CH_4$…..………………………………..…………...(6.5)

($\Delta G°$= -31.0 (kJ/mole CH_4)

Pyruvate + 4H → Propionate (C3) + H_2O + 2H

4 $Propionate^- + 3H_2O \rightarrow 4\ Acetate^- + HCO_3^- + H^+ + 3CH_4$……………………..(6.6)

($\Delta G°$= -34.0 kJ/mole CH_4)

2 C_2+ 4H → Butyrate (C4) +$2H_2O$

2 Butyrate- + $HCO_3^- + 3H_2O \rightarrow 4\ Acetate^- + CH_4 + H^+$……...…………………...….(6.7)

($\Delta G°$= -39.4 kJ/mole CH_4)

The level of hydrolysis of the synthetic wastewater was higher in winter (CODs/CODt=0.50) than in summer (CODs/CODt=0.46) as shown in **Table 6.7**. The higher hydrolysis of wastewater in winter is because the specific activity of sludge is greater under psychrophilic conditions when anaerobic systems facilitate the growth and enrichment of methanogens and acetogens (Lettinga, Rebac & Zeeman 2001). Thus, a higher CODs/CODt ratio indicates increased acidogenesis in the reactors as the CODt get converted to CODs. Conversely, a decrease in the CODs/CODt ratio is due to some CODs (based on VFA) being converted to methane. These observations are in agreement with the observations made by (Alptekin 2008).

Table 6.7: Percentages of hydrolysis and acidification of CODt and acidification of CODs based on the influent synthetic wastewater into the ABF columns.

	Dimensionless parameters[1]	Winter	Summer
Acidified fraction	VFA^2/COD_t	5%	8%
Acidified fraction of CODs	VFA/COD_s	9%	17%
Hydrolysed fraction	COD_s/COD_t	50%	46%

[1]: The dimensionless parameters are based on Alptekin (2008)); [2]: VFA is expressed in terms of influent total volatile acids (measured as acetate) and converted to COD with a factor of 1.07 (Yuan, Sparling & Oleszkiewicz 2011).

Hydrolysis and acidification are rate-limiting indicators for anaerobic digestion. The VFA/CODs ratio indicates the degree of acidogenesis, representing the amount of solubilised organic matter converted to VFA (Alptekin 2008). High VFA/CODs above 0.80 indicate that hydrolysis and acidification have reached a rate-limiting condition (Maharaj 1999). In the present study, using synthetic wastewater, the ratio was calculated to be less than 0.80 both in winter (0.09) and summer (0.17) indicating that the hydrolysis and acidification had not become rate-limiting. This was also supported by the optimal effluent COD removal, resulting in final COD below 125 mg/L from a starting influent CODs of 215 mg/L (refer to **Figure 6.2**).

Due to insignificant difference of media sizes and its TVAs, the relative performance between the media types are discussed, not the media sizes.

Reducing HRT from 20 h to 6 h, a decrease in CODs and VFA was observed, as shown in **Table 6.8,** which was unexpected. However, the growth of methanogenic bacterias is not inhibited (Lettinga & Van Haandel 1994) probably due to stable pH ranging between 7.2 - 7.4 achieved by dosing with $NaHCO_3$.

Under 20 h and 12 h HRTs, a more significant proportion of COD removal is attributed to the methanogenic activity in the ABF columns than under HRTs of 8 h and 6 h. When HRT was reduced to 8 h, generation of total volatile acids increased along with an incremental increase in effluent CODs. While under HRT of 6 h, the generation of total volatile acids decreased (refer to **Table 6.8**) and a small decrease in effluent CODs was observed (refer to **Figure 6.2**). This decrease in the total volatile acids under the HRT of 6 h indicated an increase in methanogenic activity. During the acidification phase under the 6 h HRT, some methanogens grow and start consuming VFA. Under shorter HRTs, the VFAs in CODs are degraded by the bacterial communities into soluble intermediates which serve as substrates for the next subsequent stage of anaerobic digestion (Alptekin 2008). This was indicated by reduced total volatile acids in the effluent under the HRT of 6 h compared to the HRT of 12 h (refer to **Table 6.8**).

The low effluent TVA in SFs indicated the better removal of COD due to the presence of micropores and microelements on its surface. Next to SFs, BFs showed better reduction due to the charred surface of the bamboo, providing better polarity for the development of biofilm.

The PFs showed poor removal since the surfaces are devoid of micropores and charred surface. The CF had better reduction compared to PFs.

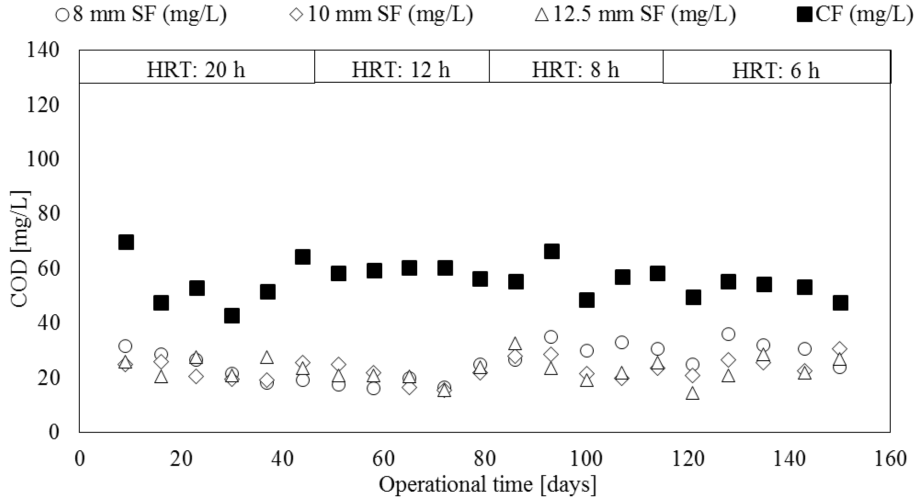
Table 6.8: Effluent TVA in biofilters (SF, PF, CF, and BF) using synthetic wastewater under decreasing HRTs.

Filters	SFs			PFs			CF	BFs		
Size→	8 mm	10 mm	12.5 mm	3 mm	5 mm	7 mm	10.5 mm	1/8 bead	1/4 bead	1/2 bead
HRT ↓	Effluent TVA (mg/L) under a constant influent TVA of 19 mg/L									
20 h	11.25	16.65	15.75	29.90	35.70	30.00	22.80	32.90	27.90	33.45
12 h	27.10	27.80	29.55	30.90	38.55	34.90	26.30	36.15	35.35	36.55
8 h	37.10	34.90	34.30	44.55	42.10	39.75	36.25	39.05	38.45	39.95
6 h	15.50	18.00	22.20	20.55	25.55	26.50	20.30	20.75	23.95	21.50

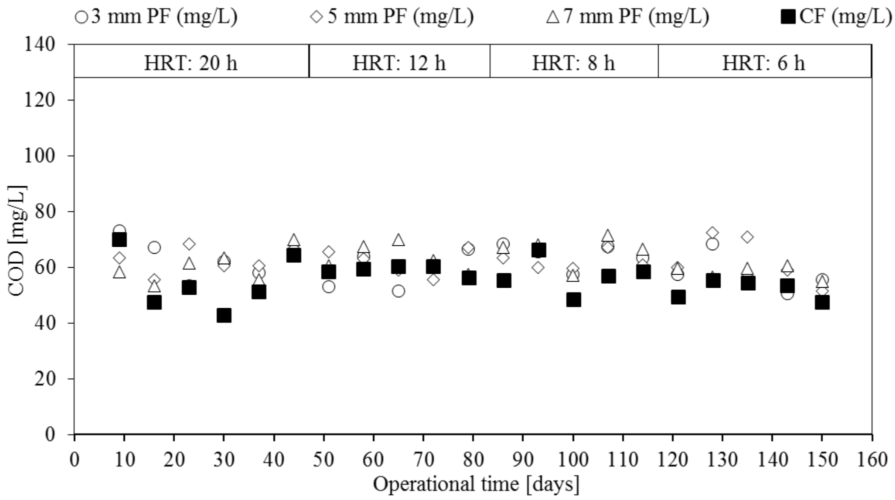
6.3.3 Performance of biofilters using synthetic domestic wastewater

6.3.3.1 COD removal and biogas yield

The synthetic influent COD into the ABF columns was kept constant at 215 mg/L. The measured effluent COD from the ABF columns is shown in **Figure 6.2**.



(a)



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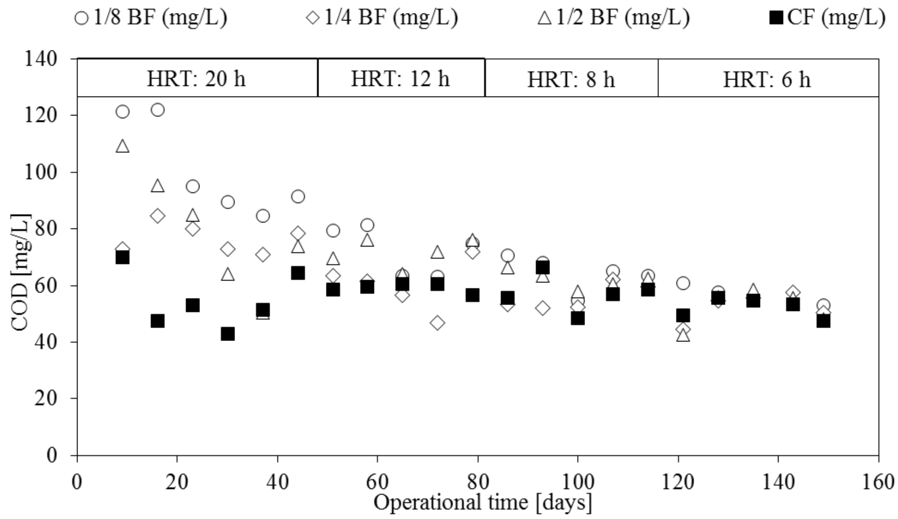


(c)

Figure 6.2: Effluent COD concentration from (a) SFs; (b) PFs; and (c) BFs, under the decreasing HRTs with a steady influent COD (215 mg/L).

Under the 20 h HRT, the effluent COD reduced as a result of high contact between the biomass in the columns and the substrates in the synthetic feedwater. As expected, the effluent COD removed an average of 74% by the commercial filter. The effluent COD was relatively lower with the SFs (< 125 mg/L, average 90% removal) than with the PFs (average 71% removal) and BFs (average 60% removal). This is assumed to be due to better biofilm development on the micropores on the surface of the slags. The higher effluent COD in PFs could be due to insufficient substrates reached to sludge inside the column attributed to low up-flow velocity under the HRT of 20 h. The comparatively higher effluent COD from BFs is attributed to the break-up of carbon particles from the surface of the semi-charred bamboo beads (Karadag et al. 2015). In summary, at HRT 20 h, SF outperformed all other media, including the CF.

After achieving consistent COD removal under the HRT of 20 h over seven weeks, the intermediate organic loading was increased by reducing HRT to 18 h, 16 h operated over a week and finally to HRT of 12 h at 5 - 6 week intervals to avoid shock loading in the columns.

At 12 h HRT, the SF still outperformed the other media despite the decreased HRT. Reduced effluent COD was achieved by the other local media, though it appears that break up of carbon particles continued to take place in BFs and the effluent COD did not stabilise. However, for CF, the effluent COD increased, assumed due to disruption of mobilised biomass due to increased up-flow velocity. At 12 h HRT, the local biofilters performed better than the commercial filter for COD removal.

At HRT of 8 h, the effluent COD increase measured for SFs and PFs could be due to dislodged substrates resulting from increased up-flow velocity. Even so, the SF continued to perform better than the PFs or BFs. The effluent COD in BFs started to reduce the COD limit of 125 mg/L. It seems the break-up of carbon particles from the surface of BFs then stabilised. COD removal in CF was better than PFs and much better than BFs. The inadequate COD removal in PFs and BFs could be due to the low growth of bacteria in poorly mixed channels giving rise to plugging thereby increasing the dead space in the reactors (Samson, Van den Berg & Kennedy 1985). Possibly the inadequate removal of COD is also attributed to the increased synthetic influent COD content compared to the decreased real domestic wastewater influent. Notably, the gradual reduction of effluent COD in BFs could have resulted due to the absence of short-circuiting effect under low or reduced HRTs applied (Samson, Van den Berg & Kennedy 1985), unlike the steady effluent of COD in SFs and PFs.

Finally at HRT 6 h, although effluent COD increased in all media, the best performing configuration for each media still met the COD limit, 14.5 mg/L in 12.5 mm SF, 50 mg/L in 3 mm PF, 47.5 mg/L in 10.5 mm CF and 42.5 mg/L in 1/2 bead BF. This indicates that the treatment of domestic wastewater by ABF can achieve the COD limits under a relatively short HRT. Under HRT of 6 h, the SFs continued to outperform the other media for COD removal. The PF and BF performance were comparable and better than to the designed CF.

The ability of the biofilter medium to maintain biosolids within the matrix of the media is more important than the unit surface area available for biomass growth or biofilm production, according to the comparison of effluent CODs between SFs, PFs, and BFs. Under the HRT of 6 h, the PFs achieved better removal (average removal 72%) than the waste bottles plastic flakes (67%) for the treatment of domestic wastewater (Dorji et al. 2021). Due to the narrowed pore packed volume in PFs as plastic bundles, the suspended biomass trapped between the media appears to have enabled the substantial removal of organic matter. The observed performance of semi-charred bamboo beads is in agreement with the performance of whole and cut rings of bamboo used for the treatment of sewage by others (Camargo & Nour 2001).

Throughout reducing HRTs, the performance of media of different sizes in each of the biofilters varied. Under the longer HRT of 20 h, the smaller media size of SFs and BFs achieved better removal of COD. This corroborates that more porous media provides better performance at higher OLR or shorter HRTs as the literature suggests (Karadag et al. 2015). Similarly, for the PFs, the best COD reduction was observed for the thinnest strips, 3 mm, which provided the largest specific surface area with low porosity. Under the shorter HRT of 8 h and 6 h, larger media size of SFs and BFs with high porosity achieve better removal of COD. Thus, it appears high surface area and low porosity in the domain of PFs influenced the treatment; while the larger media sizes and high porosity in the domain of SFs and BFs influenced the treatment. In both the cases, it appears that the media size type influenced the COD removal.

During this study, biogas production from the biofilters was insignificant. Insignificant biogas production is likely due to low organic content in the influent (average COD: 215 mg/L). The influent is designed to represent a mixture of UASB blackwater effluents and domestic greywater since most of the biodegradable organics in blackwater would have already been removed in the UASB. The measured NH_3-N was below 50 mg/L, which is far below the standard low concentration of 500 mg/L (Rajagopal, Massé & Singh 2013) which would have impeded methanogenic microbial growth. Previous studies with a low influent COD of less than

300 mg/L have reported little biogas production (Ayaz et al. 2012; Leitão et al. 2006). Whatever CH_4 that may have been produced may also have dissolved due to the low temperature of the wastewater, 16 - 21°C in winter and 21 - 28°C in summer.

6.3.3.2 Nutrient removal

The effluent NH_3-N was significantly higher than the influent NH_3-N in all the media as shown in **Table 6.9**. This increase in effluent NH_3-N is in agreement with results elsewhere found in the literature (Demirer & Chen 2005).

At 20 h HRT, the observed production of NH_3-N was greatest, presumably because protein degradation is higher at longer HRTs. In general, effluent NH_3-N was lowest at HRT 8 h for all filter media, though the results from the different media varied widely. However for all HRTs and all media, effluent NH_3-N was greater than influent NH_3-N, but since the values of NH_3-N were less than 50 mg/L, it is considered non-toxic (Rajagopal, Massé & Singh 2013).

Table 6.9: Effluent NH_3 in biofilters (SF, PF, CF, and BF) using synthetic wastewater under the decreasing HRTs.

Filters	SFs			PFs			CF	BFs		
Size →	8 mm	10 mm	12.5 mm	3 mm	5mm	7 mm	10.5 mm	1/8 bead	¼ bead	½ bead
HRT ↓	Effluent NH_3 (mg/L) under a constant influent NH_3 of 19 mg/L									
20 h	41.3	40.2	40.5	41.2	39.9	41.2	40.9	42.6	40.7	42.3
12 h	39.5	38.3	40.1	39.8	40.0	41.7	39.0	37.8	37.5	38.2
8 h	36.8	36.8	38.2	38.7	40.3	38.7	35.5	36.9	37.1	35.0
6 h	39.9	40.7	38.9	40.0	41.5	40.3	39.8	39.2	38.2	37.9

As shown in the effluent TKN in **Table 6.10,** the measured effluent NH_3-N/TKN ranged between 0.85 - 0.99 during the decreasing HRT. Typical NH_3-N/TKN for domestic wastewater ranges between 0.60 - 0.77 for different cities (Mahmoud 2002). The increased NH_3-N/TKN in the effluent is attributed to the almost doubling of NH_3-N. The increased NH_3-N in the effluent can be explained by the anaerobic biological conversion of proteins to amino acids and then to ammonia (NH_3) (Kobayashi, Stenstrom & Mah 1983).

Table 6.10: Effluent TKN in biofilters (SFs, PFs, CF and BFs) using synthetic wastewater under the decreasing HRTs.

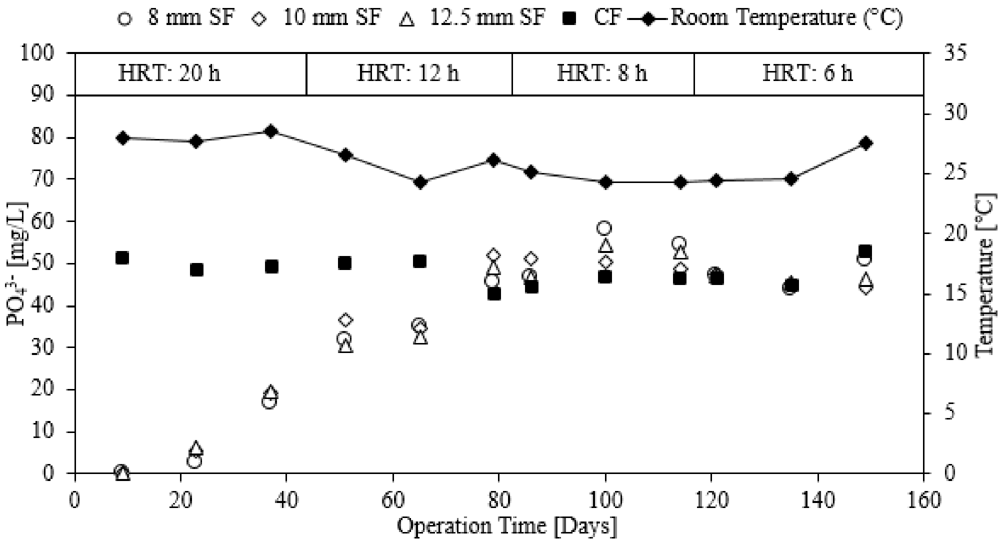
Filters	SFs			PFs			CF	BFs		
Size→	8 mm	10 mm	12.5 mm	3 mm	5 mm	7 mm	10.5 mm	1/8 bead	¼ bead	½ bead
HRT↓	TKN (mg/L) under a constant influent TKN of 48 mg/L									
20 h	44.9	42.5	43.9	44.1	47.1	44.8	43.6	45.1	43.4	43.8
12 h	40.9	39.5	40.9	40.5	41.2	42.3	39.9	39.7	38.4	39.4
8 h	37.7	37.8	38.9	39.6	41.4	38.9	36.7	38.6	38.1	36.3
6 h	41.1	41.2	41.0	41.4	43.2	41.9	40.3	41.0	39.9	39.8

With an influent TKN of 48 mg/L, the maximum removal of TKN under the various HRTs were SFs: 6.5 - 21.5%; PFs: 1.9 - 19.5%; CF: 9.2 - 23.5%, and BFs: 6 - 24.4%. The low removal of TKN from the ABF columns are in agreement with the literature and removal efficiency of 10.3% observed by others (de Oliveira Cruz et al. 2013).

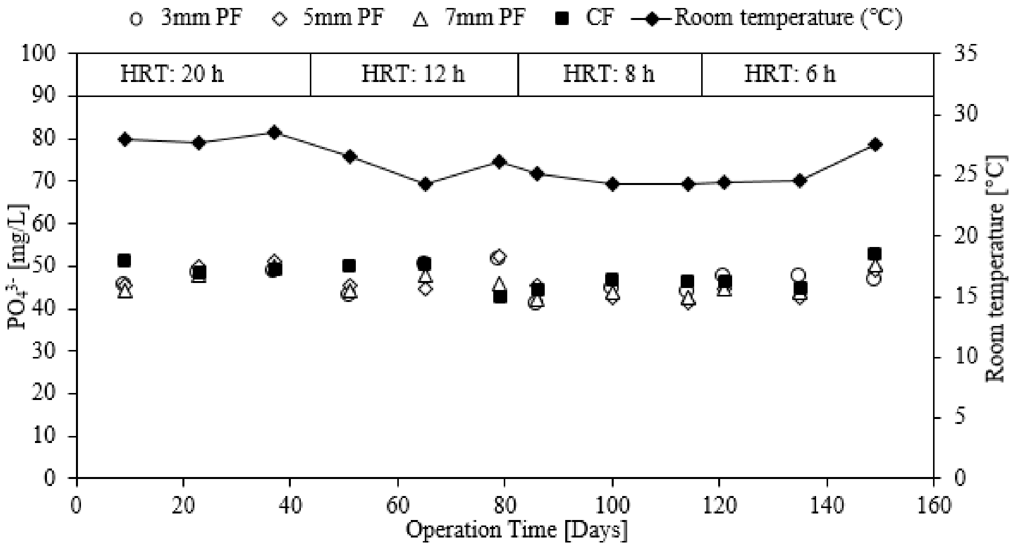
Over the different operating HRTs with a synthetic influent PO_4^{3-} of 43 mg/L, the removal of ortho-phosphate (PO_4^{3-}) remained quantitatively unchanged (refer to **Figure 6.3 (b) & (c)**) for the PFs and BFs. For the SFs, the effluent PO_4^{3-} decreased under the initial HRT of 20 h, attributed to adsorption of PO_4^{3-} on the micropores on the surface of the slags. There was no significant difference in effluent PO_4^{3-} between the different SF sizes. The removal of PO_4^{3-} by the SFs was initially above 99.7% and decreased to 18.6% under the HRT of 6 h, attributed to clogging of micropores over the operational period.

Under the influent PO_4^{3-} of 43 mg/L and HRT of 20 h, 12 h, 8 h and 6 h, removal of PO_4^{3-} from the PFs were up to 4.9% and BFs up to 9.7%. However, the CF removed only up to 0.70%, which indicated the better removal of PO_4^{3-} by the local biofilters.

The low reduction observed for removal of PO_4^{3-} is expected since anaerobic digesters are known to have a negligible impact (Demirer & Chen 2005). While treating heavy synthetic wastewater effluents, the removal of phosphorous did not exceed 19% in anaerobic biofilters of plastic and clay media (Rebah et al. 2010).



(a)



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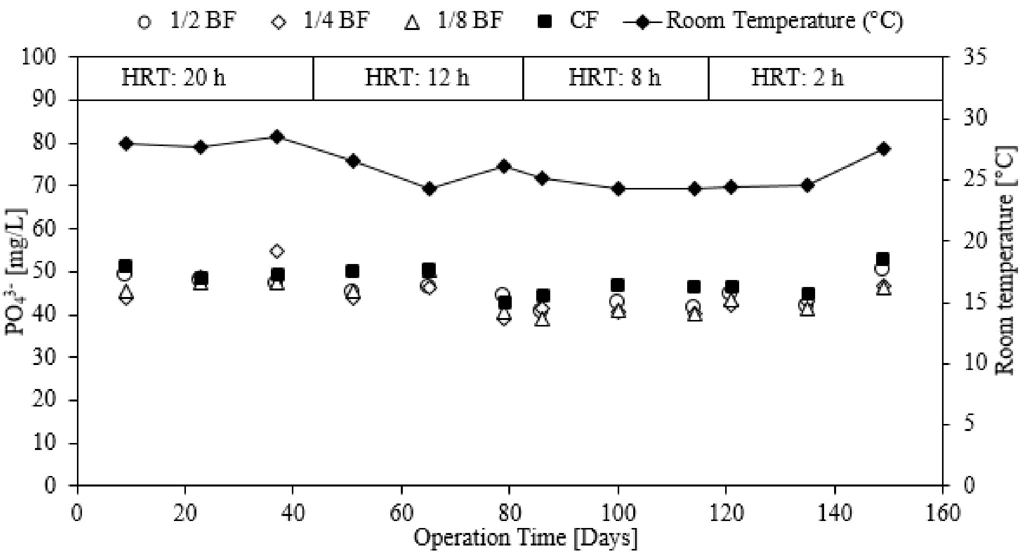


(c)

Figure 6.3: Effluent PO_4^{3-} from (a) SFs (b) PFs (c) BFs over the operation period under the decreasing HRTs and ambient room temperature.

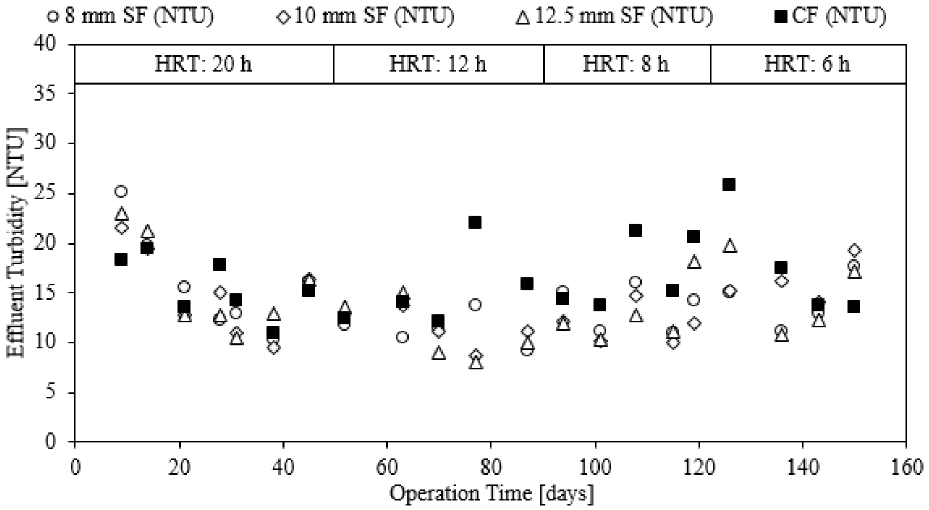
No association between the PO_4^{3-} removal and HRT could be correlated. However, PO_4^{3-} removal appears to have slightly influenced by the ambient temperature (refer to **Figure 6.3**).

6.3.3.3 Turbidity removal

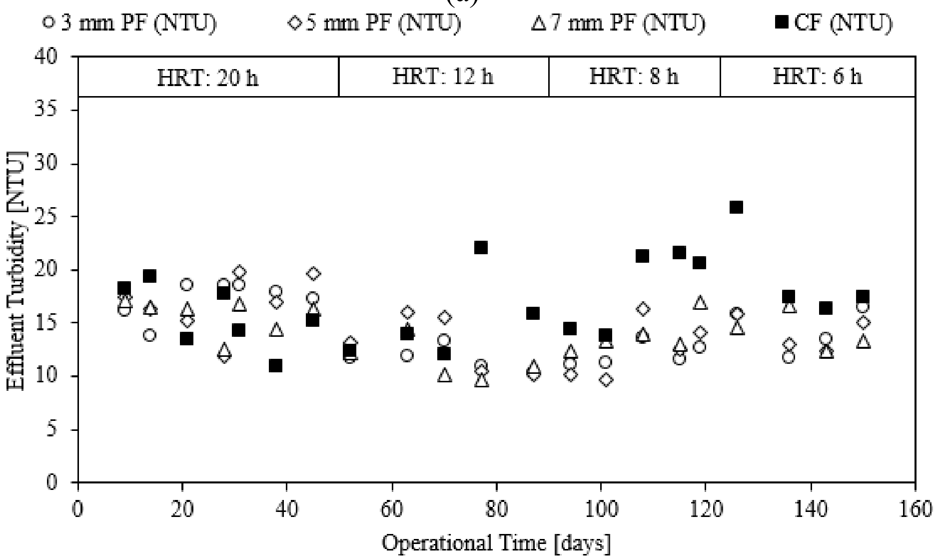
There is no turbidity limit under Bhutan's recently updated national effluent discharge standards, but a limit for TSS of 100 mg/L is given. As already mentioned, since the total suspended solids (TSS) in the ABF columns from the effluent wastewater samples were insignificant. Therefore, turbidity was measured instead to meet a target of the national standard for drinking water turbidity at 5 NTU (NEC 2016b). The effluents can be safely discharged into the streams if turbidity is less than 10 NTU (WHO 2006).

Under the initial HRT of 20 h with synthetic feedwater influent turbidity of 116 NTU, turbidity reduction was low, attributed to low up-flow velocity, whereby nutrients are not adequately removed by the biofilters (refer to **Figure 6.4**). Turbidity removal was particularly low for the BFs. Under the HRT of 12 h, the turbidity removal improved slightly, attributed to increased up-flow, transporting substrates to the biomass trapped in the biofilter voids. At the HRT 12 h, the BFs performed somewhat better than the SF and PF. However, under HRT of 8 h, the effluent turbidity increased slightly and again increased under HRT 6 h.

Although the most significant turbidity removal was achieved under the HRT of 12 h for all filter media: 8.05 NTU in 12.5 mm SF, 9.77 NTU in 7 mm PF and 1/2 bead BF. However, the limit of 5 NTU was not achieved. For turbidity removal, the local biofilters performed better than the CF (12.1 NTU) for HRTs < 20 h.



(a)



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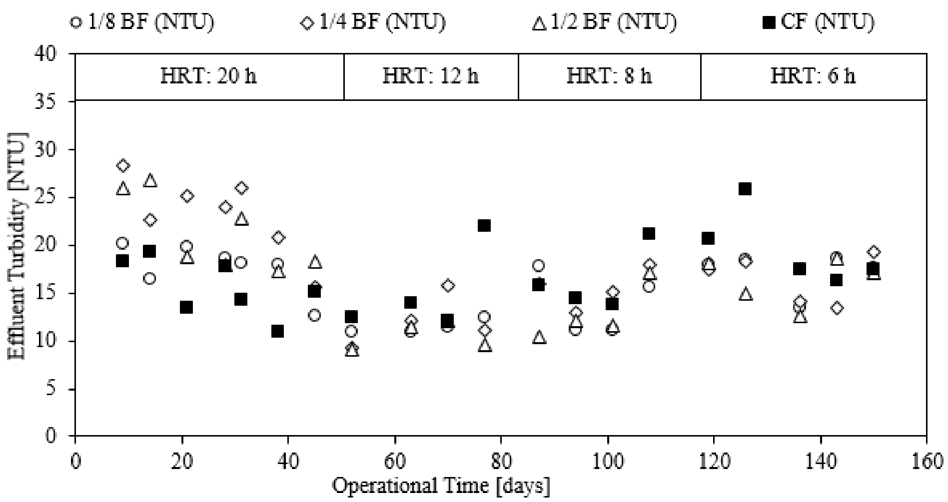


(c)

Figure 6.4: Effluent turbidity removal from (a) SFs (b) PTs (c) BFs over the operation period under decreasing reducing HRTs.

6.3.3.4 Overall performance of locally available filters treating synthetic wastewater

The 150 day test period indicated that the smaller sized SFs and BFs achieved better removal efficiency under HRT of 20 h. In comparison, the larger media size had better efficiency under the shorter HRT of 6 h (refer to **Figure 6.4**). In the case of PFs, the smaller plastic strips of 3 mm with large surface areas achieved better removal efficiency under the different HRTs. For COD removal, the SFs of all sizes outperformed the other media at all HRTs. The optimum performance was the smallest (8 mm) SF at 12 h HRT.

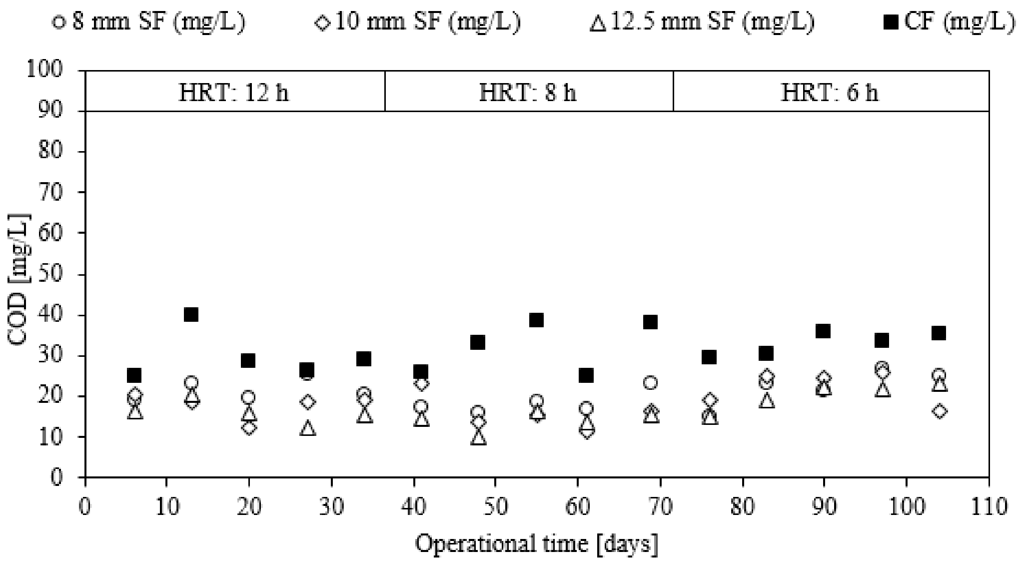
For nutrient removal, there was no apparent difference in performance between media or the different sized media. The optimum performance was by the CF, but the next best was 1/2 BF at HRT 8 h for both NH_3 and TKN. For PO_4^{3-}, SFs performed better than the others, but only in the first 80 days, after which it performed worse than the CF. The PFs and BFs of all sizes performed slightly better than the CF and did not appear to be affected by HRT.

For turbidity, the PFs performed somewhat better than SFs and BFs, but still did not meet the discharge limit at the best HRT of 12 h. Interestingly the larger SF (12.5 mm) and larger BF (1/2 ring bead) performed better than their smaller sized media. As a result of the testing with synthetic wastewater, 12 h HRT was chosen for running the systems with real wastewater but was also operated at HRT 8 h and 6 h.

6.3.4 Performance of ABF columns using real domestic wastewater

6.3.4.1 COD removal

With an influent COD of 82 mg/L, under 12 h HRT, COD removal was achieved by all media to less than the national standard of 125 mg/L (refer to **Figure 6.5)**. Optimal COD removal was achieved at HRT 8 h for all media, but the best performing was the SFs at all sizes. Even at HRT of 6 h, the effluent COD achieved 18.5 mg/L in 12.5 mm SF, 26 mg/L in 3 mm PF, 30 mg/L in 10.5 mm CF and 33.5 mg/L in 1/2 bead BF. At HRT of 6 h, the PFs and BFs performed at par with or slightly worse than the CF.



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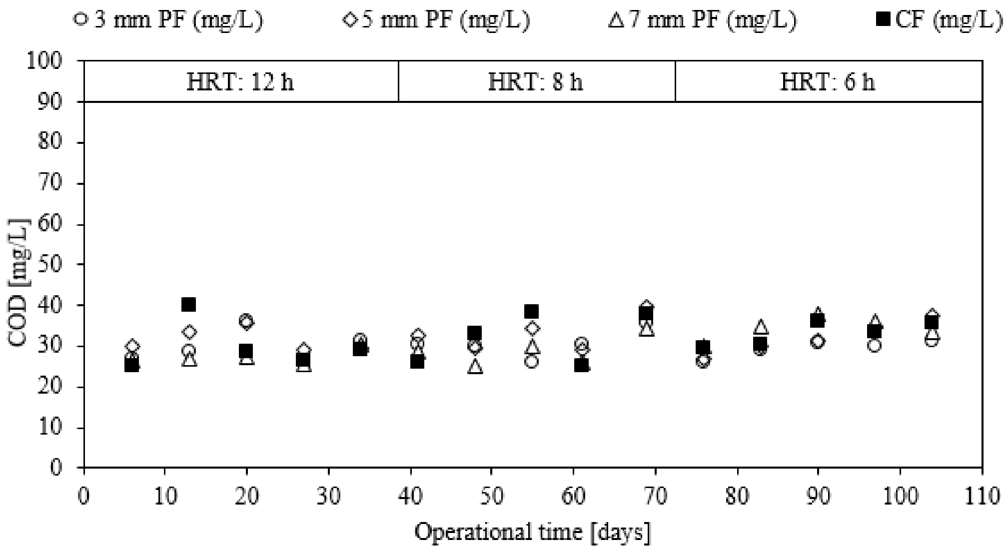

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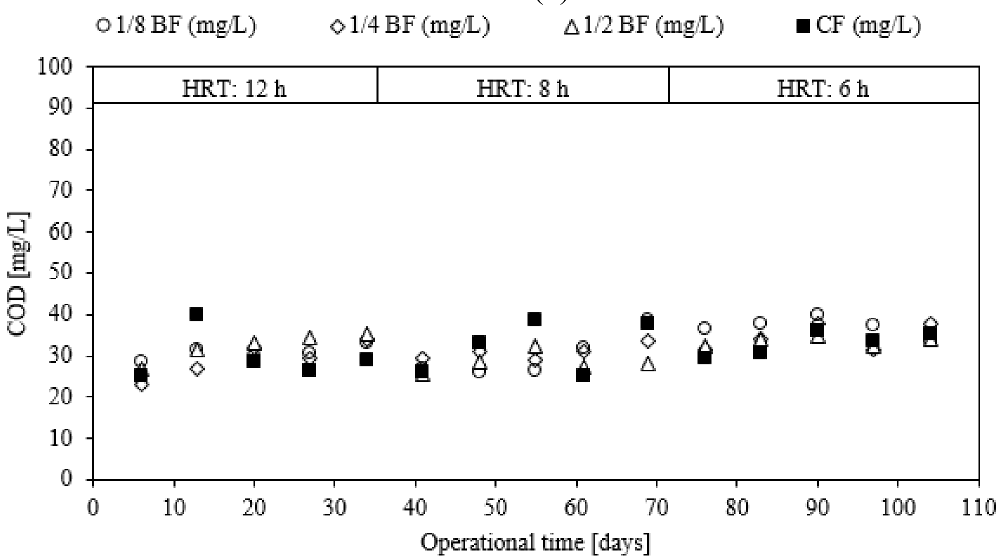

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Figure 6.5: Effluent COD concentration from (a) SFs (b) PFs and (c) BFs under decreasing HRTs.

6.3.4.2 Nutrient removal

As observed from the synthetic wastewater operation, removal of NH_3-N was found to be ineffectual at all HRTs for all media, regardless of sizes. Effluent NH_3-N was higher than the influent NH_3-N (refer to **Table 6.11)**, though both influent and effluent NH_3-N in the real wastewater was lower than for the synthetic wastewater, attributed to higher levels of dissolved nutrients in real domestic wastewater (Luostarinen & Rintala 2005). Under HRTs of 12 h, 8 h and 6 h, effluent NH_3-N concentrations ranged from 14.4 - 19.9 mg/L from an influent with average NH_3-N of 13 mg/L. Similarly, the production of methane was insignificant even at the optimal HRT of 8 h. Of the media, SF 12.5 mm and 1/4 bead BF performed best for NH_3-N and SF 10 mm performed best for TKN, all at the 8 h HRT.

Table 6.11: Effluent NH_3 in biofilters (SF, PF, CF, and BF) under the decreased HRTs.

Filters	SFs			PFs			CF	BFs		
Size→	8 mm	10 mm	12.5 mm	3 mm	5mm	7 mm	10.5 mm	1/8 bead	1/4 bead	1/2 bead
HRT ↓	Effluent NH_3 (mg/L) under an average influent NH_3 of 13 mg/L									
12 h	18.7	18.9	17.7	19.0	18.5	18.3	16.3	17.2	17.6	19.9
8 h	15.1	14.5	14.4	15.1	14.7	15.1	15.8	15.2	14.4	14.8
6 h*		15.7			17.0		16.3		16.2	

* Due to chemical shortages, tests for SFs (8 mm & 12.5 mm), PFs (3 mm & 7 mm) and BFs (1/8 bead & 1/2 bead) were no conducted.

With an influent TKN of 20 mg/L, the effluent TKN ranged between 16.38 - 22.45 mg/L (refer to **Table 6.12**). The removal of TKN was insignificant with optimum performance at less than 20% (10 mm SF at 8 h HRT). The effluent NH_3-N/TKN ratio ranged between 0.76 (8 h HRT) - 0.96 (12 h HRT).

Table 6.12: Effluent TKN in SFs, PFs, CF and BFs under the decreasing HRTs.

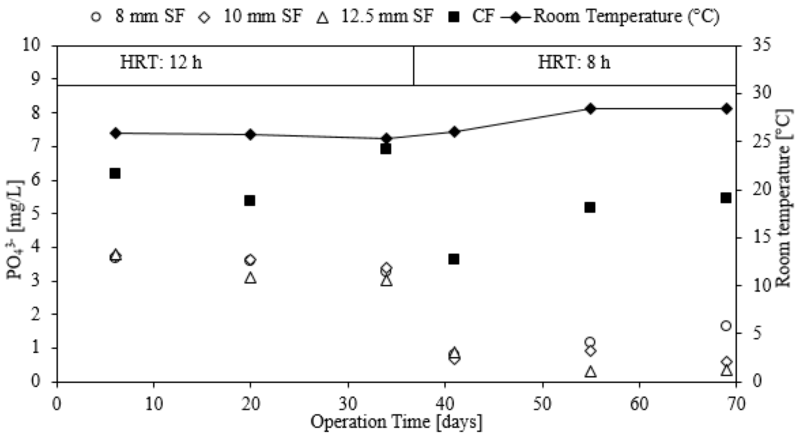
Filters	SFs			PFs			CF	BFs		
Size→	8 mm	10 mm	12.5 mm	3 mm	5mm	7 mm	10.5 mm	1/8 cut	¼ cut	½ cut
HRT↓	TKN (mg/L) under an average influent TKN of 20 mg/L									
12 h	22.45	20.00	18.93	20.42	21.05	21.02	19.58	19.10	18.17	20.60
8 h	16.62	16.38	16.85	17.65	18.50	17.77	18.00	19.08	18.10	19.42
6 h*		20.37			19.27		18.53		18.70	

* Same as mentioned above.

During operation with real wastewater, the removal of orthophosphate (PO_4^{3-}) remained quantitatively unchanged at all HRTs (refer to **Figure 6.6**). With an influent PO_4^{3-} of

4.2 mg/L, SFs of all sizes performed better than PFs and BFs, which performed comparably to the CF. The most effective was 12.5 mm SF at 8 h HRT. Due to shortages of chemicals, the results under HRT of 6 h are not shown.

Effluent PO_4^{3-} could not be correlated with the ambient temperature, unlike in the case of synthetic wastewater. This could have occurred due to the irregularity of the PO_4^{3-} content in the real mixed domestic sewage.



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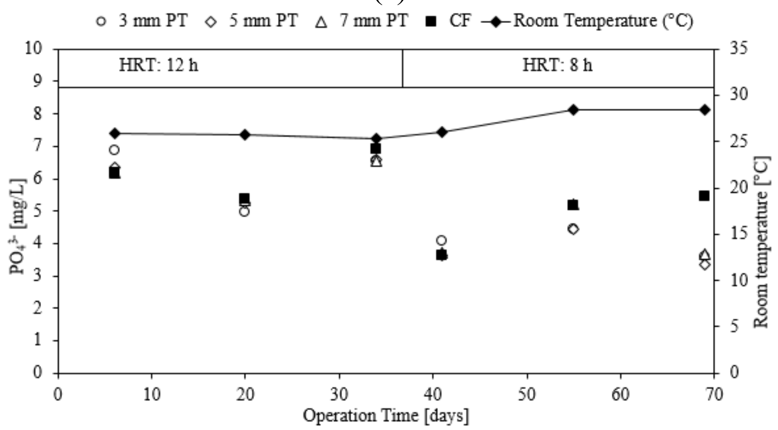

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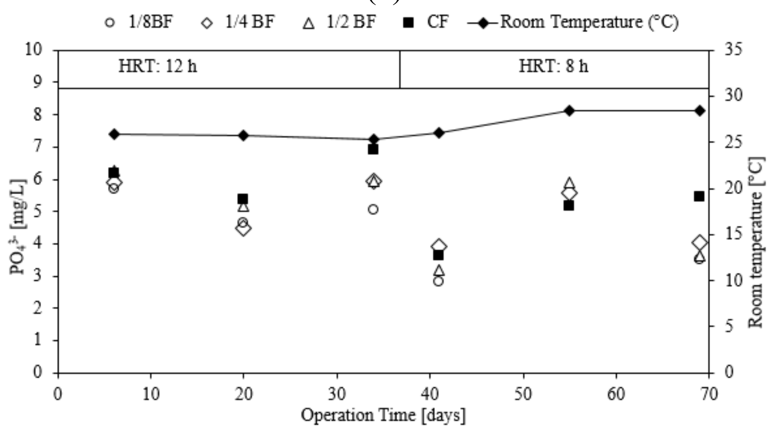

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Figure 6.6: Effluent PO_4^{3-} from (a) SFs (b) PFs and (c) BFs under decreasing HRTs.

6.3.4.3 Turbidity removal

With influent turbidity of 91 NTU, under all HRTs the effluent turbidity fluctuated substantially (refer to **Table 6.7**). The presence of detergents in real wastewater affects the turbidity as well as the toxicity (Mousavi & Khodadoost 2019) and contains more particulates than the synthetic wastewater. Though aerobic processes degrade most detergents, anaerobic digestion does not (Mousavi & Khodadoost 2019).

During the initial HRT of 12 h period, this is attributed to the introduction of the real wastewater. Decreasing effluent turbidities indicated the biomass was adapting to the real domestic wastewater. Under the HRT of 8 h the effluent turbidity measured was 14.1 NTU (12.5 mm SF), 12.2 NTU (3 mm PF), and 13.6 NTU (1/2 bead BF). The local biofilters performed no better than the commercial filter 20.1 NTU (10.5 mm CFs). In all cases, the effluent NTU exceeded the 5 NTU standard though the best values were achieved at HRT 12 h + 8 h, for the smaller PFs and BFs sizes.

The SFs did not perform as well as either PFs or BFs, but interestingly, of the SFs the larger sized media did better than, the smaller size SFs. Thus, the effect of media size, surface area and porosity on the removal of turbidity is not clear.

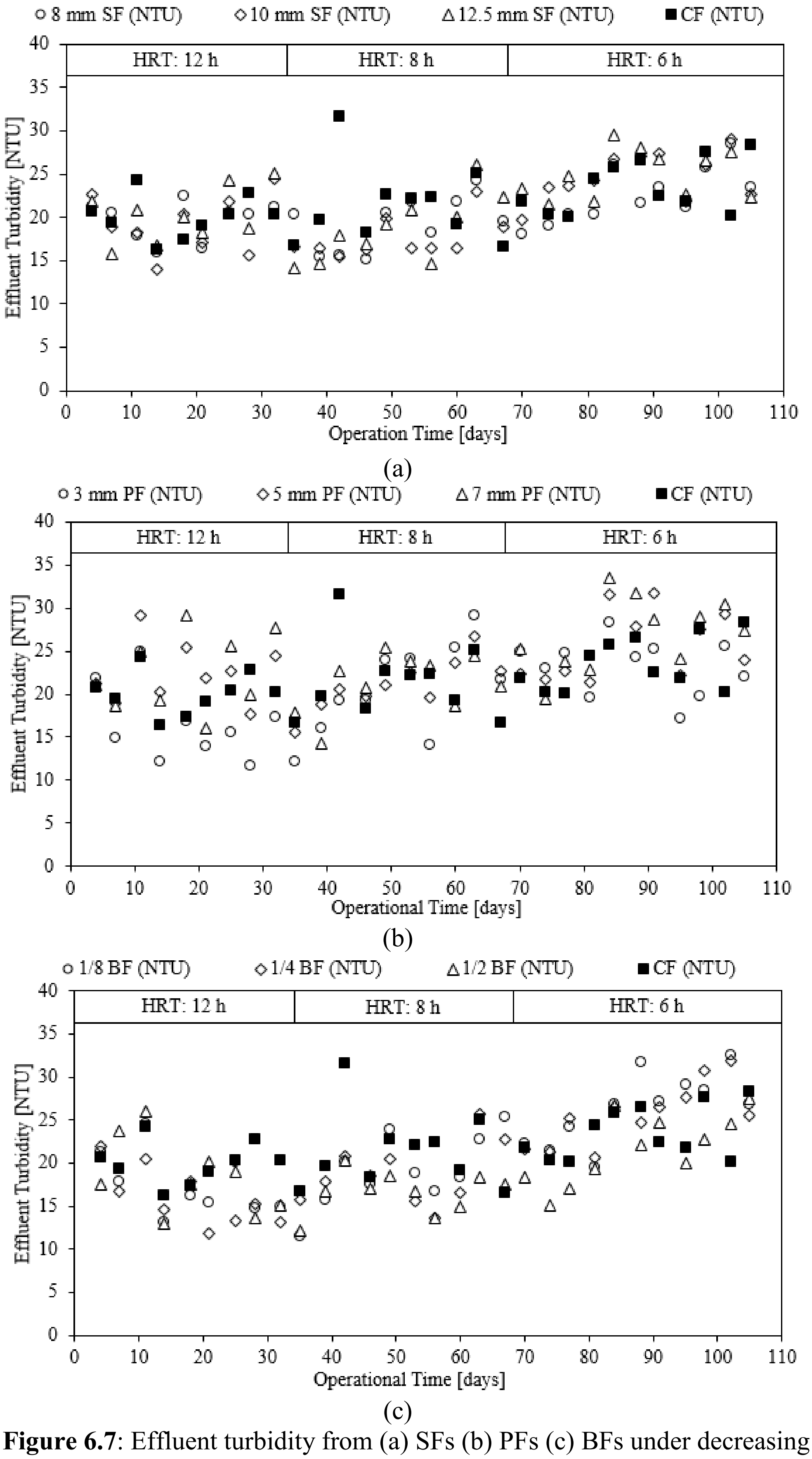

Figure 6.7: Effluent turbidity from (a) SFs (b) PFs (c) BFs under decreasing HRTs.

6.3.4.4 Overall performance of locally available filters treating real wastewater

During the 105 day test period indicated that the small-sized SFs and BFs performed better COD removal under the HRT of 12 h. In contrast, the large media size had better efficiency under the HRT of 8 h (refer to **Figure 6.5**). However, in the case of PFs, the smaller plastic strips of 3 mm with large surface areas achieved better removal efficiency under the different HRTs. For COD removal, the SFs of all sizes outperformed the other media at all HRTs. The optimum performance was observed in 12.5 mm SF at 8 h HRT.

For nutrients removal, there was no apparent difference in performance between media or the different sized media. The optimum performance was by the CF, but the next best was 1/4 BF at HRT 8 h for both NH_3 and TKN. For PO_4^{3-}, SFs performed better than the other media. The PFs and BFs of all sizes performed slightly better than the CF and did not appear to be affected by HRT.

For turbidity, the PFs performed somewhat better than SFs and BFs, but still did not meet the discharge limit at the best HRT of 12 h. Interestingly, the larger SF (12.5 mm) and larger BF (1/2 ring bead) performed better than their smaller sized media. As a result of the testing with real wastewater, under the HRT of 12 h, the performance of filters was optimal.

The biofilter life of the industrial slag and plastic strip could be extremely high (even over hundred years) which means the issue of spent biofilter is not expected. However, the life of the semi-charred bamboo could be much shorter but being organic-based media, the spent semi-charred bamboo cut containing nutrients can be used as soil amendments.

6.4 Conclusions

ABF columns with local biofilters (industrial slags, plastic strips, and semi-charred bamboo beads) were investigated and compared with a commercial filter for the treatment of UASB blackwater effluents and greywater. Three locally available materials were tested as potential ABF biofilter media, selected to provide a large surface area for COD removal via an attached-growth process and suspension of solids. Industrial slags performed better in COD removal under the optimum HRT of 12 h and 8 h, followed with mixed removals but overall better removal in plastic strips and charred bamboo beads than the commercial filters. HRT of 6 h was too low to reduce the size of the plant due to deteriorating effluent removals. Nutrients and turbidity removals need further investigation. With the addition of greywater, biogas production was negligible and cannot be claimed as a benefit. Different HRT, media size and surface area influenced the treatment capability of the biofilters. In general, the local biofilter media performed better than the commercial filter and achieved the COD (125 mg/L) discharge limit of the National Environment Commission of Bhutan. The final effluent turbidity from ABF could not reach the standard limit of water for 5 NTU; however, the effluent turbidity are safe from sewage pollution (< 70 NTU). Therefore, under the current urban settings, this study showed the potential of locally available material as biofilters for an alternative UASB+ABF combination for on-site domestic wastewater treatment for the unsewered areas of urban Bhutan.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

7.1.1 The current on-site wastewater treatment situation in urban Bhutan is inadequate

The dangers of unsafe wastewater discharges are numerous, particularly in light of climate change and ongoing contamination of freshwater sources. As a result, cost-effective treatment of wastewater must be a priority in developing countries. Rapid urbanisation in Bhutan has increased demand for alternative on-site wastewater infrastructure over conventional "septic tanks" which are often installed without soak-pits. Preliminary design, construction or operation often reduces the "septic tanks" to mere storage units providing no treatment of the wastewater. At the same time, the absence of infiltrating soak-pits leads to unsafe effluent discharge under the current urban settings.

. In Bhutan plot sizes in the urban areas are generally small because of the limited flat land available (MoWHS 2008) and this limits the space for the construction of "septic tanks" and soak-pits as per the national guidelines, as well as restricting vacuum tanker access for pit emptying due to rough terrain. Centrally operated in-situ constructed waste stabilisation ponds (WSPs) have a low unit cost but high land footprint, which is a challenge in urban areas, and particularly in Bhutan's hilly terrain. At present, only 22.8% of urban settlements are connected to a public sewerage system serving only 19.7% of the urban population. Rough assessments of the capital cost of imported package plant treatment systems find them to be expensive. However, they have a small footprint and produce superior treated wastewater effluent quality (compared to WSPs). Whole life costs for different systems; centralised wastewater treatment plants (WWTP), package plants and properly functioning "septic tanks", are not available and has not been compared.

The remaining 40.5% of buildings in the 33 classified urban towns are left without sewerage connections and rely on "septic tanks" of these 40% are without soak-pits. Loss of open space, increase in non-porous surfaces and urban regulations has led to greywater management issues, either being disposed to surface water drains or to the "septic tanks", which are not designed for its treatment. As a result, anaerobic performances of septic tanks is compromised, and tanks fill up quickly. High frequency of septic tank emptying is not only impractical (limited number of vacuum tanker in each town) but expensive and this exposes themselves and their communities to pollution, a severe risk since 80.3% of the urban population use "septic tanks". Buildings without soak-pits add to the volume of inadequately treated effluent discharged into the surroundings in addition to the free disposal of greywater. Notably, the treatment of greywater is still not considered a priority despite constituting the majority of domestic wastewater.

Although it is a national policy goal, having a fully networked sewerage systems for all the urban settlements in Bhutan will likely take time. However, this goal is also impracticable given the logistics, costs and topography involved. Accepting the reality of "septic tanks" for the interim until networked systems are built, there is a critical need for proper regulation to ensure safe management of "septic tanks". The current on-site wastewater treatment situation is inadequate, prompting an investigation of an alternative on-site treatment system, which can accommodate both black and grey water while being low tech, cost-effective and physically compact.

7.1.2 Combined UASB and ABF as an affordable alternative to current on-site wastewater treatment for modern urban settings in Bhutan

Lab-scale investigations of shredded waste plastic bottles as a low-cost filter for domestic wastewater treatment by attached growth process achieved the national COD, BOD and TSS discharge limits. Reuse of waste plastics added value by reducing direct and environmental costs associated with the management of waste plastics. The final effluent turbidity from the combined treatment system was around 5 NTU, which is generally acceptable for disposal to the environment since less than 10 NTU (WHO 2006). The lab-scale study showed that UASB combined with ABF treatment system using shredded waste plastic bottles as the biofilter media is a promising alternative for on-site treatment system for urban Bhutan.

During the full-scale pilot study, the up-flow anaerobic sludge blanket (UASB) was shown to be able to treat organic-rich blackwater, developing a stable sludge granules, achieved by up-flow hydraulics but producing negligible biogas. The use of anaerobic biofilter (ABF) with shredded waste plastic bottles for secondary treatment of UASB effluent mixed with domestic greywater also showed potential to reduce COD/BOD, with negligible production of biogas. The removal efficiencies and biogas production from this two-step on-site anaerobic treatment system demonstrated potential as an alternative treatment system to the existing conventional "septic tanks".

The biofilter media in ABF appeared to cope with high OLRs (optimum HRT between 12 - 6 h), attributed to the removal of organics by the filter matrix. Thus, this trial UASB+ABF process has potential for community wastewater treatment in unsewered urban areas, and particularly suitable for institutional buildings with populations above 50 PE.

7.1.3 Shredded waste plastic bottles as an effective and low-cost biofilter media

Anaerobic up-flow filtration through an ABF with shredded waste plastic bottles as biofilter media for the treatment of mixed UASB effluent, and greywater has the potential to be an effective option for reduction of organics. Due to the entrapment of biosolids in the filters, the influent organic loads from UASB effluents and greywater were able to be digested in the voids and surface of the shredded plastic media. The biofilm on the plastic media captured pathogens and organics, facilitated by the high surface area of the thin and curved shredded waste plastic bottles chips. Further, the robust performance of ABFs is thought to have benefitted from roughening of the plastic flakes surface to facilitate the growth of biomass on the plastic media surface.

During the year-long operation of the pilot ABF system, a compliant discharge COD of 125 mg/L was achieved, an essential preliminary milestone for testing this anaerobic ABF treatment process in Bhutan before venturing into real-scale applications. Having attempted the investigation of the treatment system for the first time in Bhutan, the pilot operation demonstrated the ability of shredded waste plastic bottles as a low-cost filter for domestic wastewater treatment via attached growth process to achieve the discharge limits in terms of COD, BOD and TSS, while having the added value of reducing waste plastic problems. Due to the nature of PET, it is expected that shredded waste plastic bottles are suitable as biofilter media due to their long life compared to organic media such as bamboo.

7.1.4 Other locally available biofilter media options for on-site wastewater treatment

Considering the local source and transportation costs; any material can be tested as a biofilter media, selecting for high surface areas to facilitate attached growth and remove dissolved organics through the biomass and biofilm formation while retaining solids. The nature and size of the chosen biofilter media should minimise short-circuiting and should have large enough pore space to avoid clogging problems during extended periods of treatment. However, added value can be claimed when the biofilter media reduces municipal waste volumes (shredded plastic waste bottles chips), is locally available (semi-charred bamboo beads) or reduces risks to the environment (industrial steel slags) in the long term. In contrast, commercial filters which are not locally available, are relatively expensive and need to be imported, making them unsuitable for the developing countries. Surprisingly, the local biofilters performed at par or better than the commercial filter investigated in this study. Therefore, considering the local context, local biofilters facilitate the affordability of the tested treatment system.

The pollutant removal potential of waste plastic bottle strips was enhanced by providing it as loose plastic bundles (like knitting yarn), which improved the retention of biosolids within the criss-crossed network of strips and voids. In addition to its lightweight nature and resistance to abrasion, plastic biofilters can be back washed easily for desludging and reused without any issue. Semi-charred bamboo beads also attained a COD effluent of 125 mg/L. In contrast, due to local availability and its biodegradable nature, used bamboo filters can be disposed of for use in the agricultural field to enrich the soil with nutrients. As for the industrial slag filters, presumably due to its porous nature, the best COD removal was achieved. Use of industrial slag filters for on-site treatment of sewage could reduce steel by-product wastes that require careful handling and disposal.

The inclusion of the locally available biofilters, i.e., the semi-charred bamboo beads and industrial steel slags have widened the identification of potential filter media.

7.2 Recommendations and future research work

7.2.1 Investigate the performance of this on-site wastewater treatment system in the colder regions of Bhutan

Anaerobic treatment of wastewater is a temperature-dependent process. During the year-long operation of the pilot treatment system, through both summer and winter, the effect of ambient temperature on the reactor performance was observed. Since the pilot was operated in the warmer southern part of the country, consideration of the colder climate in majority of other urban centres of Bhutan is needed. The impact of psychrophilic conditions on the treatment of sewage wastewater needs investigation to identify optimal HRT and get a better understanding of the performance of two-stage anaerobic treatment of domestic sewage in Bhutan. Since anaerobic treatment may not be effective under extremely cold conditions, investigation of different methods to maintain temperature should be carried out, e.g., water jacketing of bioreactors or buried/ semi-buried bioreactors to reduce effects of extreme cold temperature. Housing the system in the shed with heating is likely to prove financially unsustainable. Therefore, demonstration of the treatment system under colder conditions is needed to verify suitability as a treatment system for urban areas with different climates as an alternative to the prevailing systems of treatment on-site.

7.2.2 Process optimisation to increase the removal of E-coli from the wastewater

Although UASB and ABF systems treating domestic wastewater generally remove E.coli by one order of magnitude, the effluents still do not meet the NEC standard of Bhutan (1000 cfu/100 mL) for discharge and unrestricted irrigation. Therefore, further research is needed to verify that E.coli levels could be reduced to meet the national effluent standard proving second ABF filtration using a combination of local materials. A two stage ABF is one of the potential options that could help reduce the E-coli removal while also further improving the effluent quality. Identifying biofilter with better E-coli removal efficiency may be targeted for the second stage ABF.

7.2.3 Modular design and potential commercialisation of the UASB+ABF technology in Bhutan

To overcome the high cost of land and construction, increased use of pre-fabricated package sewage treatment plants (STPs) for treatment of domestic wastewater is found all over the world (Sharma & Kazmi 2016). Due to the compactness of package treatment plants compared to conventional treatment systems, package systems can be quickly and easily installed in crowded urban areas reducing the installation time and cost (Greaves, Thorp & Critchley 1990). Therefore, a package plant consisting of two bioreactors (UASB and ABF) could be designed, developed and operate to carry out the combined treatment of domestic BW and GW via suspended and attached growth systems. A modular package plant could be designed for construction by local factories or private vendors, using locally available filter materials, creating a local package plant fabrication industry in Bhutan and this same private vendors can also provide operation and maintenance services for all the installations in a packaged business models, supported by a strong legislation supporting private services. Due to the growing significance of decentralised treatment systems, financial support options could be provided by the government to enable the development of the technology for the country-wide application. The same entities could also install and operate the package system at individual households, commercial or institutions.

7.2.4 Installation and operation of full-scale on-site wastewater treatment system at CST campus for long-term operation and monitoring

The lab and pilot-scale treatment of domestic wastewater with UASB+ABF were investigated during this study; however, very rough financial studies found that it only became comparable to the current conventional septic tank + soak-pit system at and above PE 50. Therefore, to further verify the technology, investigation of full-scale on-site wastewater treatment is necessary for long-term operation and monitoring. The use of shredded waste plastic bottles enabled anaerobic digestion in ABF indicated by the steady removal of COD. At this scale, we might also be able to determine if biogas production levels become sufficient to heat the plant in the winter, or offset pumping electricity costs in summer. The long-term operation would provide a robust understanding of the anaerobic process and media filtration, adding significant operational and management experience under Bhutan's ambient conditions.

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APPENDIX

Chapter 3: Supplementary Material

1. Survey sampling and coverage

The survey covered 35 of 38 currently classified towns (92% coverage in terms of towns), which included four major towns, 16 district towns, and 15 (of 18) satellite towns, covering a total urban population of 251,010 (91% of the total urban population and 34% of Bhutan's total population). The survey covered a total urban area of 123.34 km^2, as demonstrated in S1.

The 35 classified towns include 4 Major Towns (total population of 161,392 and total area of 61 km^2, 6,419 buildings), 16 District Towns (total population of 61,229, total area of 42.76 km^2, 2,913 buildings) and 15 Satellite Towns (total population of 22,127, total area of 19.07 km^2 and 1,095 buildings). The survey data for the 3 Satellite Towns were not provided or unavailable during the time of this study (NSBB 2018). Thimphu City is also the largest town with an area of 26 km^2, estimated population of 114,551 and a total number of buildings about 4,874 in 2017 (NSBB 2018). Mendrelgang satellite town under Tsirang District has the lowest urban area (0.03 km^2) and population (62 people only). Damji satellite town under Gasa District has the lowest number of buildings (4 in total). The details of the survey at building-level, for the two representative towns of Thimphu and Khuruthang, are presented in Table S2 of the SM. Approximately 600 buildings were randomly identified (initially in Thimphu) for the survey, of which 510 questionnaires were returned – a response rate of 85%; however, only 493 buildings were considered complete for analysis. For Khuruthang town, 44 out of 78 buildings were covered by the survey – a coverage of 56%. This larger coverage was possible because Khuruthang is a much smaller town, with an area of only 0.42 km^2.

At Thimphu City, the sampling covered 37% of the Taba area, 29% of the Jungshina area, 23% of the Semtokha and 45% of the Babesa area, based on the total number of buildings picked up from the satellite map in these areas. Since there is no information on the population data of each of this survey region, the survey coverage regarding population for each area could not be determined. However, the survey at Thimphu covered 10.3%, 13.7% and 8% of the buildings, households, and population, respectively of the entire Thimphu City.

For Khuruthang town, 44 buildings out of 78 were covered by the survey with a coverage of 56%. This better coverage was possible because Khuruthang is a much smaller town with an area of only 0.42 km^2.

2. Survey approach for the two representative towns

Thimphu and Khuruthang were selected as representative towns for a detailed survey at the building or property level. Thimphu is the capital city was selected because of the highest concentration of the total urban population (42% of the total urban population in 2015) in Bhutan. As a representation of the other smaller District and Satellite Towns in Bhutan, Khuruthang town was selected, located at 70 km from Thimphu. The survey was conducted using structured questionnaires (Appendix 1) targeting individual building owners at the two representative towns to capture the state of the on-site sanitation system. The field surveys at the Thimphu and Khuruthang towns were conducted following the Random Sampling Method to obtain a strong representation of buildings in the survey areas.

The zonal maps and other information available for the two towns were used to target the areas for survey as shown (Figure S1). The survey focussed only on those areas or regions of the Thimphu without public sewer connections. With the help of satellite map, the buildings were randomly selected and marked in the map for interviews. Each independent building and their uses could vary such as residential, commercial, offices or mixed. Government institutions such as schools were not covered in the study. Having decided each survey area, the sample size of each survey area was calculated assuming about 85% coverage in the area. The undergraduate students from the College of Science and Technology (CST) were trained and engaged as the survey enumerators. The questionnaires were either handed over to the building owners for collection later in the day or next, while for some building, the owners were interviewed face. The survey enumerators also collected additional information from the properties or buildings such as the dimensions of the existing septic tanks, their distances from the building boundaries and their conditions at the time of the survey. The survey enumerators were divided into two the groups each group consisting of 12 enumerators. The groups visited approximately 20 buildings per day.

3. Supplementary Tables

Table 3.S1: Survey coverage of all the towns and the two representative towns in Bhutan.

Towns	**Total Nos.**	**Total urban area (km^2)**	**Total population (PHCB 2017)**	**Total buildings in the towns**	**Average annual population growth rate (%)**	**Remarks**
3 Major Thromde	3	34.99	46,841*	1545		
16 District Thromde	15	42.76	61,229*	2913	3.4%++	
18 Satellite Thromde	15	19.07	22,127*	1095		
Coverage	**33**	**96.82**	**130,197**	**5553**		
Representative towns	Thimphu	26.10	114,551*	4874#	3.7%++	Ref. **Table 3.4**
	Khuruthang	0.42	6,262*	78 ##	0.90%++	
Total cover-age	35	123.34	251,010	10,505	3.4%	

*#Based on Population and Housing Census of Bhutan or PHCB 2017 (NSBB 2018).
(Khuruthang Municipal 2017).
++ Calculated from (NSBB 2018).

Table 3.S2: Number of buildings surveyed at two representative towns.

Name of unsewered areas	Nos. of buildings estimated	Nos. of buildings surveyed	Total residential households	Total non-residential units	Total population in the survey*
Taba	302	111	639	76	1,975
Jungshina	313	90	652	64	1,900
Semtokha	455	103	571	50	1,533
Babesa	421	189	1,630	380	3,713
Thimphu survey	**1,491**[a]	**493**	**3,492**	**570**	**9,121**
Total at Thimphu	4,784[b]		20,093[c]	n/a	114,551
Thimphu coverage		10.3%	13.7%		8%
Khuruthang survey	**78**[d]	**44**	**234**	**134**	**485**
Total	**1,569**	**537**	**3,726**	**704**	**9,606**

*Survey population data based on the field survey
[a] Based on clustered map of Thimphu Thromde (2016).
[b] Data from the recent PHCB report (NSBB 2018).
[c] based on mean household size in Thimphu (NSBB 2018).
[d] Data provided by Punakha Dzongkhag Thromde (2016).

Table 3.S3: Analysis of the WWT technologies currently applied in Bhutan.

	Thimphu	**Phuentsholing**	**Gelephu**	**Dechencholing**	**Samtse**	**Ministerial Enclave**	**Bajo**	**Damphu**	**Gyelpoishing**	**Khuruthang**	**Samdrup Jongkhar**	**Trashigang**	**MHPA**
Year of construction	**1996**	**1996**	**2008**	**2013**	**2016**	**2010**	**2012**	**2008**	**2009**	**2017**	**2013**	**2008**	**2015**
1. Waste Water Treatment Plant (WWTP)													
1.1 Type of WWTP	WSP	WSP	WSP	MBBR	DEWAT	Ecoline	Ecoline	Ecoline	Ecoline	Ecoline	Ecoline	Ecoline	Ecoline
1.2 Actual area covered by WWTP (m^2)	50,221.53	30,472.86	18,575.09	140.00	3,035.15	11.34	24.00	23.89	26.45	22.56	37.10	70.00	21.00
1.3 Actual area covered by WWTP (Acres)	12.410	7.530	4.590	0.035	0.750	0.003	0.006	0.006	0.007	0.006	0.009	0.017	0.01
1.4 Maximum treatment capacity (MLD)	1.750	2.157	3.321	0.750	0.500	0.0460	0.2760	0.1380	0.1380	0.4140	0.2300	0.0736	0.0920
1.5 Maximum population equivalent (PE) capacity	12,500	13,950	36,098	8,152	5,435	500	3,000	1,500	1,500	4,500	2,500	800	1,000
1.6 Total cost of WWTP (million US$)	0.480	0.343	0.534	0.545	0.227	0.125	0.350	0.188	0.182	0.449	0.388	0.085	0.313
1.7 OR Total cost of WWTP (million BTN)	31.000	21.952	34.190	34.900	14.522	8.000	22.419	12.0000	11.64	28.730	24.85	5.4290	20.000
1.8 Current inflow rate to the WWTP (MLD)	1.535	1.720	2.250	0.096	-	0.024	0.940	0.130	0.080	0.080	0.280	0.1040	0.016
1.9 Current working capacity (%)	88%	80%	68%	13%	-	52%	341%	94%	58%	19%	122%	141%	17%
2. Sewer network													
2.1 Total sewer lines main & branch (km)	-	9.50	11.50	-	1.30	6.45	2.87	0.51	1.50	2.17	11.50	0.79	2.00
2.2 Total cost of the sewer network (million US$)	6.516	4.657	0.41	-	0.08	0.02	0.13	0.19	0.03	0.15	0.15	0.01	0.01
2.3 Total cost of the sewer network (million BTN)	417.00	298.05	26.23	-	5.00	1.50	8.00	12.00	1.90	9.40	9.60	0.66	0.70
2.4 Total Buildings currently connected to sewer lines	-	1,153	350	-	-	42	131	48	16	68	162	66	13
2.5 Total household units currently connected to sewer lines	-	-	1,400	-	-	42	1,048	245	96	408	486	233	17
2.6 Total population currently connected to sewer lines	-	-	8,000	-	-	146	5,240	1,225	2,000	1,632	3,500	1,000	100
3. Capital, Operation & Maintenance costs, Sewerage revenue													
3.3 Source of funding for the project	DANIDA	DANIDA	DANIDA	World Bank	RGoB	RGoB+GoI	RGoB	RGoB	RGoB	GoI	RGoB/GoI	RGoB	GoI
3.1 Annual O&M costs of the WWTP (million US$)	0.01719	0.01563	0.00156	0.00375	-	0.00500	0.00313	0.00453	0.00781	-	0.00781	0.00620	0.00078
3.1 Annual O&M costs of the WWTP (million BTN)	1.10	1.00	0.10	0.24	-	0.32	0.20	0.29	0.50	-	0.50	0.40	0.05
3.2 Annual O&M costs for sewer network (million BTN)	-	5.00	0.50	-	-	0.20	0.20	0.24	1.00	1.00	0.20	0.15	0.01
3.3. Sewage tariff in 2017 (US$/$m^3$)	-	0.01	0.02	-	-	0.03	0.01	0.01	-	0.01	-	0.01	-
3.3. Sewage tariff in 2017 (BTN/m^3)	-	0.40	1.27	-	-	2.18	0.75	0.50	-	0.75	-	0.40	-
3.3. Annual revenue from sewage tariff 2017 (million Nu)	-	12.945	0.600	-	-	0.121	0.276	0.033	-	-	-	0.032	-
4. Analysis													
4.1 WWTP area per unit capacity (m2/MLD)	28,698.019	14,127.425	5,593.221	186.667	6,070.290	246.522	86.957	173.116	191.667	54.493	161.304	951.087	228.261
4.2 WWTP area per unit population (m^2/person)	4.02	2.18	0.51	0.02	0.56	0.02	0.01	0.02	0.02	0.01	0.01	0.09	0.02
4.3 Capital cost of WWTP (million US$/MLD)	1.06	0.61	0.32	1.01	0.48	4.78	1.96	2.68	2.25	4.88	2.35	2.31	3.91
4.4 Capital cost of WWTP (million BTN/MLD)	17.71	10.18	10.30	46.53	29.04	173.91	81.23	86.96	84.35	69.40	108.04	73.76	217.39
4.5 Total capital cost of WWTP+network (million US$/MLD)	4.00	2.32	0.28	-	0.61	3.23	1.72	2.72	1.53	1.44	2.34	1.29	3.52
4.6 Total capital cost of WWTP+network (million BTN/MLD)	256.000	148.354	18.193	-	39.044	206.522	110.214	173.913	98.116	92.109	149.783	82.690	225.000
4.7 Capital cost of WWTP (US$/person)	38.400	24.588	14.799	66.892	41.751	250.000	116.766	125.000	121.250	99.757	155.313	106.035	312.500
4.7 Capital cost of WWTP (BTN/person)	2,480	1,574	947	4,281	2,672	16,000	7,473	8,000	7,760	6,384	9,940	6,786	20,000
4.8 Capital cost of sewer network (US$/person)	521	334	11	-	14	47	42	125	20	33	60	13	11
4.8 Capital cost of sewer network (BTN/person)	33,360	21,365	727	-	920	3,000	2,667	8,000	1,267	2,090	3,840	821	700
4.9 Total capital cost of WWTP+network (US$/person)	560	358	26	-	56	297	158	250	141	132	215	119	323
4.9 Total capital cost of WWTP+network (BTN/person)	35,840	22,939	1,674	-	3,592	19,000	10,140	16,000	9,027	8,474	13,780	7,608	20,700
4.10 O&M cost of WWTP (US$/$m^3$ of treated WW)	0.031	0.025	0.002	0.107	-	0.571	0.009	0.095	0.268	-	0.076	0.163	0.134
4.10 O&M cost of WWTP (BTN/m^3 of treated WW)	1.96	1.59	0.12	6.85	-	36.53	0.58	6.11	17.12	-	4.89	10.46	8.56
4.11 Total O&M WWTP +cost of WWTP+network (BTN/m^3 of treated WW)	292.57	186.63	26.90	-	-	409.17	32.57	186.85	175.50	-	124.82	62.34	1,296.88
4.12 Revenue/O&M cost ratio	-	12.95	6.00	-	-	0.38	1.38	0.11	-	-	-	0.08	-

Table 3.S4: Summary of the on-site sanitation system in all the municipal areas of Bhutan. IST: individual septic tank. SP: soak-pit. BTN: Bhutan Ngultrum (1 US$ ~ BTN 70).

Specifications	Thimphu	Khuru	Major Towns	District Towns	Satellite Towns	All towns	Major Towns (%)	District Towns (%)	Satellite Towns (%)	Total %
Total number of towns covered	1	1	3	15	15	35				
Total number of buildings in the town	4874	78	6419	3146	1095	15612				
Total buildings connected to public sewer system	1601	68	3266	409	315	5659	43.10%	15.16%	28.77%	36.2%
On-site sanitation system:										
Total buildings with IST & SP	1,096	11	2,539	2,456	1,024	7,128	39.9%	79.57%	64.77%	50%
Total buildings with IST & no SP	1,839	63	2,949	484	486	5,821	46.3%	15.67%	30.74%	40%
Total buildings with other sanitation system	337	4	882	147	71	1,441	13.8%	4.76%	4.49%	10%
Total buildings with onsite sanitation system	***3,273***	***78***	***6,371***	***3,087***	***1,581***	***14,390***	100%	100%	100%	100%
Septic tank sludge management:										
Towns with one vacuum truck			4	12	1		50%	71%	8%	
Towns with no vacuum truck			-	4	12		-	24%	92%	
Total			***8***	***17***	***13***		***100%***	***100%***	***100%***	
Sludge management practices:										
WWTP			4	4	-	8	100%	19%	-	22.2%
Landfill disposal			-	11	5	16	-	52%	45%	44.4%
No proper facilities (disposed near rivers)			-	2	3	5	-	10%	27%	13.9%
No proper facilities (other disposal)			-	4	3	7	-	19%	27%	19.4%
Total			***4***	***21***	***11***	***36***	***100%***	***100%***	***100%***	100.0%
Average septic tank cleaning cost (BTN/ST)		3000	1,750	1,333	2,750					
Average septic tank truck cleaning cost (BTN/truck)		1000	1,833	1,797	2,025					
Cost of Ecoline® cleaning (BTN/year)	468,000		-	150,000	-					

Table 3.S5: Analysis of the septic tank based on the dimensions provided in the (MoWHS-SNV 2013). WW: wastewater, BW: Blackwater, GW: greywater. Q: flow rate

No. of users	L (m)	W (m)	H (m)	V_e (m^3)	WW (L/p/d)	BW (L/p/d)	Q_{ww} (L/d)	HRT (d)	Q_{BW} (L/d)	HRT (d)
5	1.5	0.75	1.3	1.01	92	20.4	460	2.2	102	9.9
10	2.0	0.9	1.3	1.62	92	20.4	920	1.8	204	7.9
15	2.0	0.9	2.0	2.88	92	20.4	1380	2.1	306	9.4
25	2.6	1.3	1.8	4.73	92	20.4	2300	2.1	510	9.3
50	4.0	1.4	2.0	8.96	92	20.4	4600	1.9	1020	8.8
75	5.0	1.5	2.0	12.00	92	20.4	6900	1.7	1530	7.8
100	5.7	2.1	1.7	15.56	92	20.4	9200	1.7	2040	7.6

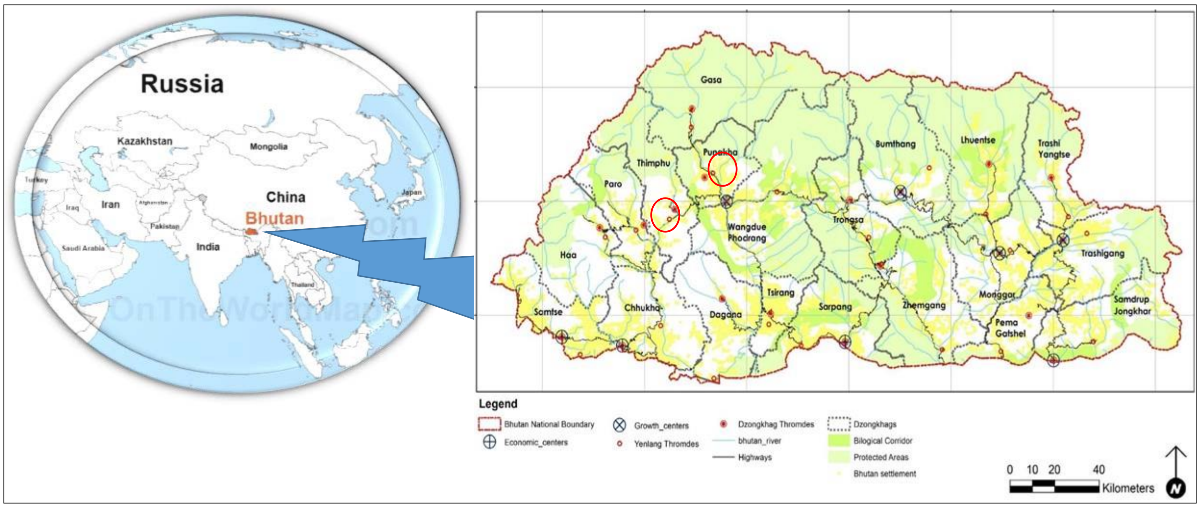
Table 3.S6: Survey response for the questionnaire "who constructed the septic tanks?"

Design	Thimphu (n=470)	Khuruthang (n=44)
Qualified engineer (includes degree, diploma and certificate)	66%	50%
Just constructed on own specification	17%	11%
Standard design and drawings provided by City Corporation	4%	34%
Just constructed by the contractor	10%	5%
Don't know	3%	0%
Construct		
Self	34%	59%
Contractor	62%	36%
Others	0%	2%

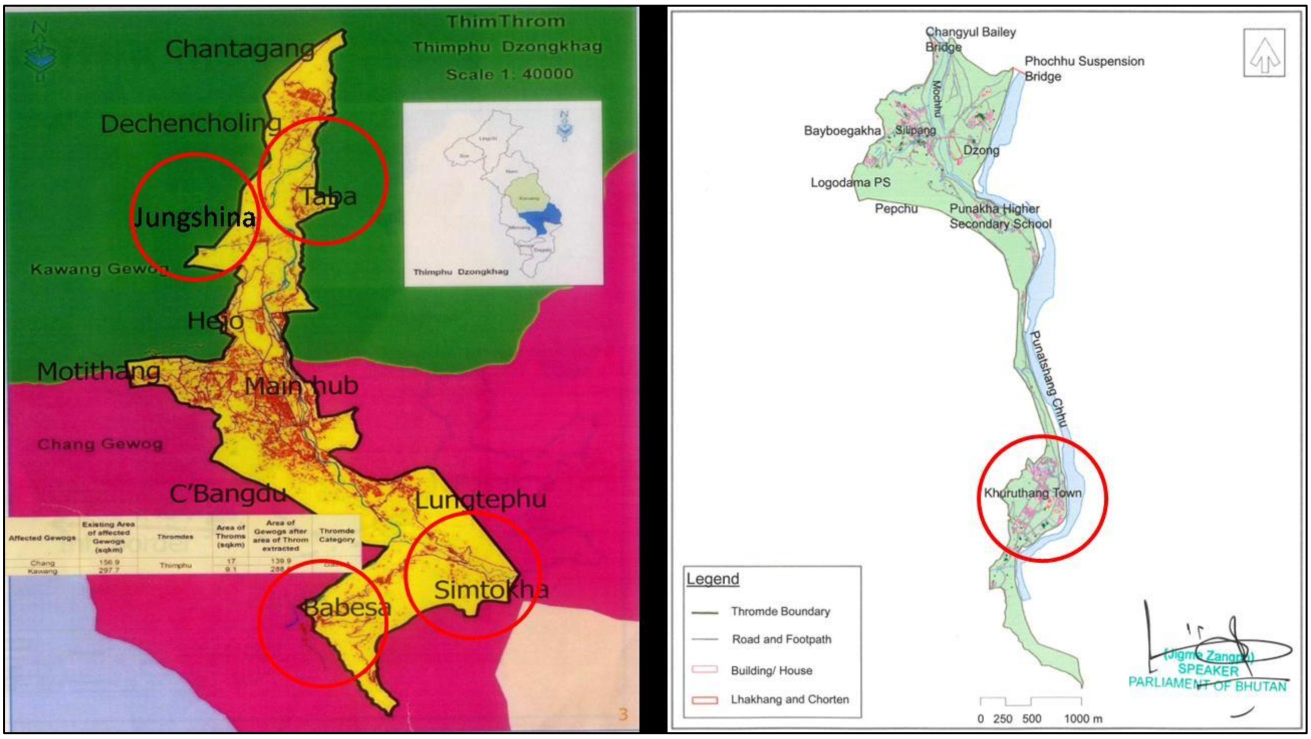
Table 3.S7: Space analysis of surveyed buildings

Detail survey parameters	Thimphu (n=85)	Khuruthang (n=32)
Plot area		
Maximum plot area (m^2)	1600.00	518.40
Minimum plot area (m2)	96.00	187.69
Average plot area (m^2)	514.66	296.40
Built-up areas or plot coverage		
Minimum built up area coverage (%)	10.14%	27.95%
Maximum built up area coverage (%)	68.08%	66.74%
Average built up area coverage (%)	41.31%	52.61%
Open space or unbuilt area on the plot		
Minimum area of plot unbuilt (m^2)	65	82
Maximum area of plot unbuilt (m^2)	820	230
Average area of plot unbuilt (m^2)	290	140
Building setback from the plot boundaries		
Rear setback		
Minimum rear set back (SB) (m)	1.0	1.0
Maximum rear set back (SB) (m)	8.0	4.2
Average rear set back (SB) (m)	3.3	2.2
Front setback		
Minimum front set back (SF) (m)	1.0	1.5
Maximum front set back (SF) (m)	8.0	4.9
Average front set back (SF) (m)	4.6	2.8
Left side setback		
Minimum left side set back (SL) (m)	1.0	1.0
Maximum left side set back (SL) (m)	8.0	4.8
Average left side set back (SL) (m)	3.4	2.0
Right side setback		
Minimum right side set back (SR) (m)	1.0	1.3
Maximum right side set back (SR) (m)	8.0	6.5
Average right side set back (SR) (m)	3.7	2.0

APPENDIX 3.1: Map of Bhutan with the location the two survey towns.



APPENDIX 3.2: Map of Thimphu City and Khuruthang City with the areas of the survey.



APPENDIX 3.3: Household field survey questionnaires

Assessment of on-site wastewater management in the unsewered areas of Thimphu and Khuruthang.
Dear Sir/Madam, Under the grant of Bhutan Trust Fund for Environmental Conservation (BTFEC), the College of Science and Technology (CST) in collaboration with the University of Technology Sydney (UTS) in Australia is conducting a survey to study the conditions and efficiency of the existing on-site sanitation system in the un-sewered areas of Thimphu, and Khuruthang (selected as sample town). The survey is anonymous and will be used strictly for the purpose of the research only with strictest confidentiality. We would like to thank you for agreeing to participate in our questionnaire survey. **PLEASE ANSWER THE QUESTIONS BELOW:**

Plot and Building Details

1. Location.
   (a) Town:______________
   (b) Survey Zone Code: ________________
2. Usage of the building/house surveyed.
   (a) If residential only.
   Number of households in the building: _______
   Total number of people living in the whole building (if known):_______
   (b) If commercial only.
   Number of commercial/business units: _____
   Total number of people working/living in the whole building (if known): _____
   (c) Mixed or multiple purposes.
   Number of commercial units: _______
   Number of residential units: _______
   Number of offices: ____________
   Total number of people living in the building (if known):________
   (d) Offices only.
   Number of offices: ______
   Total number of people working in all the offices (if known):______
3. Plot sizes and dimensions (refer the diagram below).
   3.1 Plot area: ______ decimals
   3.2 Plot boundary length (PL): _______ m
   3.3 Plot boundary width (PW): _______ m
   3.4 Setback front (SF): _______ m
   3.5 Setback right (SR): _______ m
   3.6 Setback left (SL): _______ m
   3.7 Setback back (SB): _______ m
4. Year in which the building was built:_________/don't know

On-site Sanitation Details

5. What type of on-site sanitation system do you have?
   (a) Septic tank with soak-pit
   (b) Septic tank without soak-pit
   (c) Pit latrines
   (d) No private sanitation system
   (e) Don't know
6. Who designed and provided the drawings for the on-site sanitation system?
   (a) Qualified Engineer (includes degree, diploma and certificate)
   (b) Just constructed on own specification
   (c) Standard design and drawings provided by the City Corporation
   (d) Just constructed by the contractor
   (e) Don't know
7. Septic tank information (refer the diagram below).
   7.1 Septic tank length of 1st chamber (STL1): _______ m
   7.2 Septic tank length of 2nd chamber (STL2): _______ m
   7.3 Septic tank width: _______ m
   7.4 Septic tank depth (STd): _______ m
   7.5 Distance of septic tank from building (STb): _______ m
   7.6 Septic tank from property boundary (STp): _______ m
   7.7 Design capacity of the septic tank: ________ users/not sure
   7.8 Year when the septic tank was constructed: ________/don't know
   7.9 Who constructed the septic tank?
   (a) Self
   (b) Contractor
   (c) Others: __________________________
   (d) Don't know
   7.10 Materials used for septic tank construction
   (a) Reinforced cement concrete (RCC)
   (b) Stone or brick masonry walls with RCC roof slab
   (c) Others: ___________________________________
   7.11 Do you have any issues with the septic tanks?
   (a) Yes (b) No
   7.12 If yes, what are the types of issues you encountered with the septic tanks? Choose one or more.
   (a) Over flowing of septic tank
   (b) Bad odour from the septic tank
   (c) Attraction of flies
   (d) Blockage of the septic tanks
   (e) Collapse of the septic tank walls
   (f) Collapse of septic tank top slab
   (g) Leakage of septic tanks
   (h) Others if any:____
   7.13 How accessible is the septic tank for cleaning services?
   (a) Easily accessible to the vacuum tanker
   (b) Moderately accessible to vacuum tanker
   (c) Accessible with difficulty
   (d) Inaccessible to the cleaning services
   7.14 Have you ever cleaned your septic tank?
   (a) Yes (b) No (c) Don't know
   7.15 When do you decide to request for the cleaning service for your septic tank?
   (a) Whenever it over flows
   (b) From time to time
   (c) Don't know
   7.16 When was the last time your septic tank was cleaned?
   (a) Less than 6 months ago

(b) 6 – 12 months ago
(c) 1 – 2 years ago
(d) 2 – 3 years ago
(e) More than 3 years ago
(f) Don't know when

7.17 How often do you clean the septic tank using the City service?
(a) Once every 6 months
(b) Once every year
(c) Once every 2 years
(d) Once every 3 years
(e) Don't know

7.18 How much do you pay for each septic tank cleaning service?
Nu. ______________ per service

7.19 What do you think about the amount charged by the city for the cleaning service?
(a) Cheap
(b) Affordable
(c) Expensive and needs to reduce to Nu. _____________ per cleaning service

7.20 Are you satisfied with the cleaning services provided by the city?
(a) Yes satisfactory
(b) Not satisfied with their services and reasons: -
____
(c) Don't know

7.21 Usage of the area on the top of the septic tank
(a) Car parking
(b) Nothing but left empty
(c) Green areas

7.22 Current condition of the septic tanks as inspected on the day of survey:
(a) Over flowing
(b) Leakage
(c) No visible issues observed

8. Soak-pit information (if any) (refer the diagram below).

8.1 Number of soak-pits: __________
8.2 Soak-pit diameter (SPd): ______________ m
8.3 Distance of soak-pit from building (SPb): __________ m
8.4 Distance of soak-pit from property boundary (SPb): _________ m
8.5 Materials used soak-pit materials?
(a) Broken bricks
(b) Stone aggregates
(c) Others: _______________________________

8.6 How is top of the soak-pit area used now?
(a) Green areas (grass/lawn/any plantations)
(b) Hard pavement such as concrete, bricks
(c) Car parking
(c) Soft open ground and no parking

8.7 What is the current condition of the soak-pit area?
(a) Wet and muddy appearance
(b) Rich vegetation such as grass grown
(c) Others describe: ____

8.8 Have you ever experienced complaints about the issues related to septic tank/soak-pit?
(a) I complained to the neighbour about their issues affecting me.
(b) My neighbour complained to me about my issues affecting them.
(c) I have heard other neighbours complaining each other about affecting the other.

9. What do you think about your current on-site sanitation system?
(a) I think it works properly.

(b) I feel that it does not work properly and need an improved system.
(c) I don't know.

10. Do you know how much did it cost to construct your on-site sanitation system?
    (a) Nu.______________.
        What is your opinion about this cost?

        a. It is expensive and unaffordable.
        b. It is affordable.
        c. We can afford more expensive one if it is more efficient than current one.

    (b) I don't know.
11. What do you think if your on-site sanitation system does not work properly?
    (a) Don't really care much.
    (b) I am helpless.
    (c) I feel concerned.
        a. Why do you feel concerned?
            i. Because it is not good for my health
            ii. Because it is not good for the public health
            iii. Because it can pollute the soil and the water
            iv. Don't really know
12. Constructing public sewage collection network and sewage treatment plant is very expensive for the government. Hence, it may likely take many years for everyone in the city to have public sewerage connections. In such a case, there are much more improved on-site sanitation technologies compared to the existing one which are expensive. CST with UTS is currently doing a research to explore which type of technology is more suitable, efficient and affordable for urban areas of Bhutan.

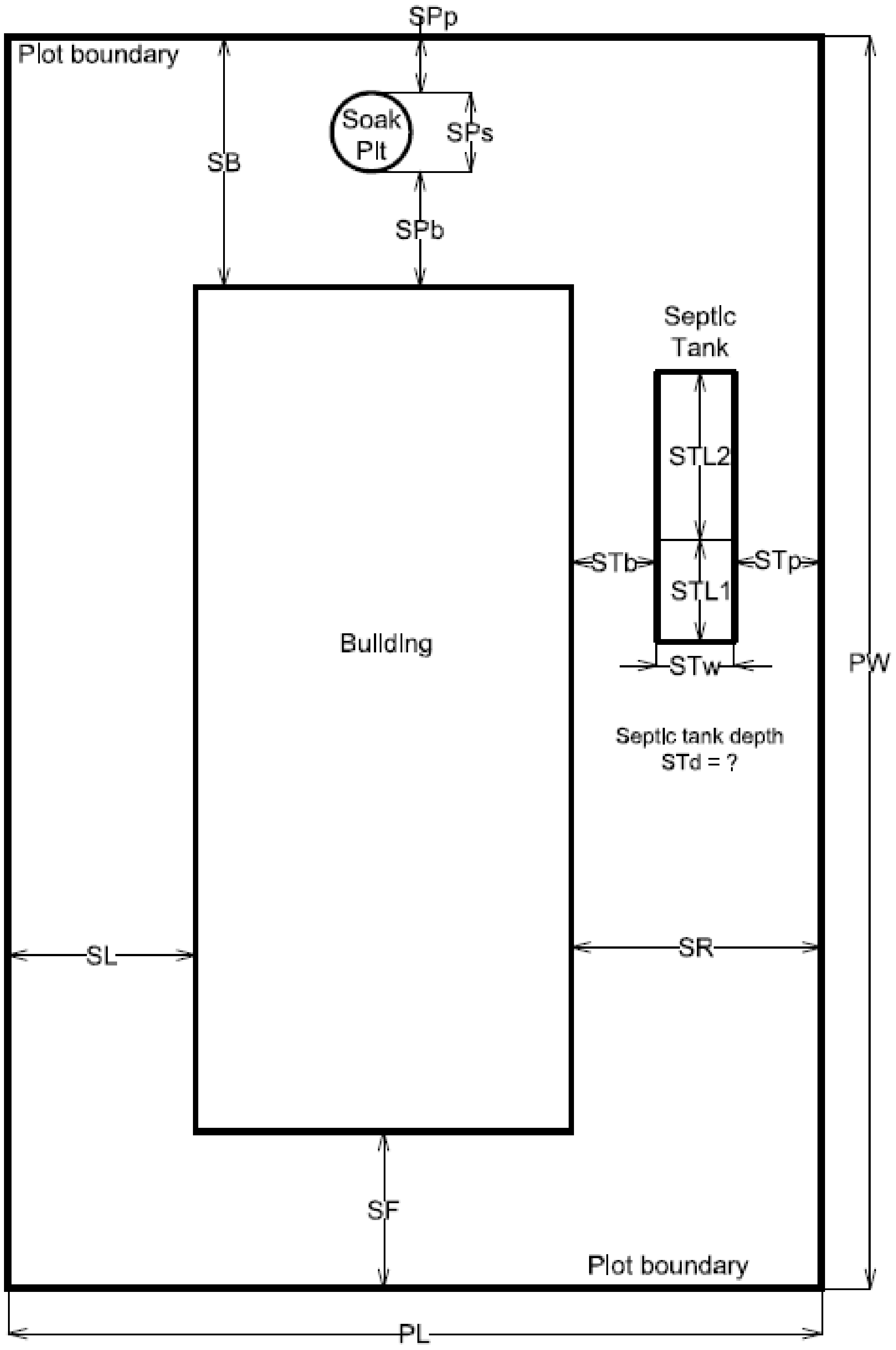
    However, such improved technology will cost more than the current system as it is not environmental friendly.

    Are you ready to accept such technology?
    (a) No, I don't know.
    (b) Yes, I think so if it can improve the environment.
    (c) Yes, I think so as long as it is not very expensive.
    (d) Yes, I think so but the government must provide some subsidy.

    Are there markets for such technology?
    (a) No, I don't know.
    (b) Yes, I think so if it can improve the environment.
    (c) Yes, I think so as long as it is not very expensive.
    (d) Yes, I think so but the government must provide some subsidy.

    Can community afford such technology?
    (a) No, I don't know.
    (b) Yes, I think so if there are loans from banks.
    (c) Yes, I think so as long as it is not very expensive.
    (d) Yes, I think so but the government must provide some subsidy.

    Such technology will bring social benefits in terms of employment such as fabrication and production?
    (a) No, I don't know.
    (b) Yes, I think so.



PL= Plot boundary length
PW= Plot boundary width
SF= Setback front
SR= Setback rlght
SL= Setback left
SB=Setback back

STL1= Septlc tank length of 1st chamber
STL2= Septlc tank length of 2nd chamber
STw= Septic tank width
STb= Dlstance of septlc tank from bulldlng
STp= Septlc tank from property boundary
SPd= Soak plt dlameter
SPb= Distance of soak pit from building
SPb= Dlstance of soak plt from property boundary

Chapter 5: Supplementary Material

1. Supplementary Tables

Table 5.S1: Economic analysis of conventional "septic tank".

		Septic tank + Soak pit					
Capital cost							
Users	PE	15	25	50	75	100	Remarks
Cost of RCC septic tanks	Nu	39,697	50,771	72,271	89,141	108,165	BSR 2020
Soak pit cost	Nu	6,482	6,482	46,562	46,562	46,562	
Start up cost (1 d TA + truck)	Nu	2,500	2,500	3,000	3,000	3,000	
Total capital cost	**Nu**	**48,679**	**59,753**	**121,833**	**138,703**	**157,727**	
Annual interest rate (%)	%	10%	10%	10%	10%	10%	
Years of life	y	30	30	30	30	30	
CAPEX (Nu/month)	**Nu/m**	**427**	**524**	**1069**	**1217**	**1384**	
CAPEX (Nu/pp/month)	**Nu/pp/m**	**28**	**21**	**21**	**16**	**14**	
O&M cost							
Desludging volume	m^3	2.88	4.73	8.96	12	15.56	
Desludging rate	Nu/m^3	1,000	1,000	1,000	1,000	1,000	
Desludging cost (every 2 years)	Nu	2,880	4,730	8,960	12,000	15,560	
Total O&M costs (Nu/y)	**Nu/y**	**1,440**	**2,365**	**4,480**	**6,000**	**7,780**	
OPEX (Nu/month)	**Nu/m**	**120**	**197**	**373**	**500**	**648**	
OPEX (Nu/pp/month)	**Nu/pp/m**	**8**	**8**	**7**	**7**	**6**	
Summary							
CAPEX	Nu/m	427	524	1,069	1,217	1,384	
OPEX	Nu/m	120	197	373	500	648	
Total monthly expenditure	Nu/m	547	721	1,443	1,717	2,033	
Total monthly expenditure	Nu/p/m	36.48	28.86	28.85	22.90	20.33	
Total monthly expenditure	Nu/HH/m	153.21	121.21	121.17	96.16	85.37	

Table 5.S2: Economic analysis of improved on-site wastewater treatment system.

		UASB + ABF improved on-site system				
Capital cost						
Users	PE	15	25	50	75	100
UASB reactor						
Black water generation	L/d	300	500	1,000	1,500	2,000
HRT of UASB	d	2	2	2	2	2
UASB reactor size	m^3	0.60	1.00	2.00	3.00	4.00
Cost of RCC septic tanks BSR	Nu	39,697	50,771	72,271	89,141	108,165
Septic tank volume	m^3	2.88	4.73	8.96	12	15.56
Unit cost of RCC tanks	Nu/m^3	13,784	10,734	8,066	7,428	6,951
Total cost of UASB tank (cf: 1.5)	Nu	8,270	10,734	16,132	22,285	27,806
Cost factor for UASB reactor	Nu	1.5	1.5	1.5	1.5	1.5
Actual cost of UASB tank	Nu	12,405	16,101	24,198	33,428	41,709
Anaerobic biofilter						
Grey warer generation	L/d	1,200	2,000	4,000	6,000	8,000
HRT of ABF	d	0.37	0.37	0.37	0.37	0.37
Media porosity	%	70%	70%	70%	70%	70%
Actual ABF reactor volume	m^3	0.63	1.05	2.10	3.14	4.19
Unit cost of RCC tanks	Nu/m^3	13,784	10,734	8,066	7,428	6,951
Total cost of ABF tank	Nu	8,664	11,245	16,900	23,346	29,130
Cost factor for ABF tank	Nu	1.5	1.5	1.5	1.5	1.5
Actual cost of ABF tank	Nu	12,996	16,867	25,350	35,020	43,695
Waste plastic biofilter media						
Cost of plastic collection	Nu/kg	18	18	18	18	18
Shredding cost	Nu/kg	2.00	2.00	2.00	2.00	2.00
Total plastic media required	kg	54.05	90.08	180.15	270.23	360.30
Total cost of plastic media	Nu	1,081	1,802	3,603	5,405	7,206
Earth works						
UASB Earth works	m^3	0.60	1.00	2.00	3.00	4.00
ABF Earth works	m^3	0.63	1.05	2.10	3.14	4.19
Total earthwork	m^3	1.23	2.05	4.10	6.14	8.19
Rate of earth work (Nu/m3)	Nu/m^3	146.61	146.61	146.61	146.61	146.61
Total cost of earthwork	Nu	180	300	600	901	1,201
Start up operations						
Total start-up cost	Nu	7,000	7,000	8,000	8,000	8,000
Summary of capital costs						
Actual cost of UASB tank	Nu	12,405	16,101	24,198	33,428	41,709
Actual cost of ABF tank	Nu	12,996	16,867	25,350	35,020	43,695
Total cost of plastic media	Nu	1,081	1,802	3,603	5,405	7,206
Earthworks	Nu	180	300	600	901	1,201
Total start-up cost	Nu	7,000	7,000	8,000	8,000	8,000
Total capital cost	**Nu**	**33,662**	**42,070**	**61,751**	**82,753**	**101,811**
Annual interest rate (%)	%	10%	10%	10%	10%	10%
Years of life	y	30	30	30	30	30
CAPEX (Nu/month)	**Nu/m**	**295**	**369**	**542**	**726**	**893**
O&M cost						
Desludging volume	m^3	1.23	2.05	4.10	6.14	8.19
Desludging rate	Nu/m^3	1,500	1,500	1,500	1,500	1,500
Desludging cost (every 2 years)	Nu	1,843	3,071	6,143	9,214	12,286
Desludging costs	Nu/month	77	128	256	384	512
Monitoring cost (0.5 d/month)	Nu/month	500	500	500	500	500
OPEX (Nu/month)	**Nu/month**	**577**	**628**	**756**	**884**	**1,012**
Summary	Users	15	25	50	75	100
CAPEX	Nu/m	295	369	542	726	893
OPEX	Nu/m	577	628	756	884	1,012
Total monthly expenditure	Nu/m	872	997	1,298	1,610	1,905
Total monthly expenditure	Nu/p/m	58.15	40	26	21	19
Total monthly expenditure	Nu/HH/m	244.22	167.52	109.02	90.17	80.03

Table 5.S3: Total month expenditure per houshold per month for conventional, improved and DEWATS system.

Users	Conventional	Improved	DEWATS
	Nu./HH/month		
15	153	244	141.91
25	121	168	141.91
50	121	109	141.91
75	96	90	141.91
100	85	80	141.91