Lipid Degradation Behavior in the Application of the Intermittent Contact Oxidation Process

その他のタイトル	間欠接触酸化法の適用における脂質分解挙動
学位授与年月日	2018-08-31
URL	http://hdl.handle.net/2261/00078757

東京大学大学院新領域創成科学研究科
社会文化環境学専攻

2018年度
修士論文

Lipid Degradation Behavior in the Application of the Intermittent Contact Oxidation Process
間欠接触酸化法の適用における脂質分解挙動

2018年7月13日提出
指導教員　佐藤　弘泰　准教授

Sotelo, Tiffany Joan Del Rosario
ソテロ ティファニージョアンデルロサリオ

ACKNOWLEDGEMENTS

I have very few words to say to convey my immense thankfulness towards everyone who supported me during the development and completion of this study.

First, I would like to express my gratitude to my supervisor, Assoc. Prof. Hiroyasu Satoh, for the unprecedented belief, support, and guidance he has extended to me throughout the duration of this study. Thank you for your patience in revising my drafts, in evaluating my presentations, and in listening to my experimental mishaps for the last two years. Thank you for not giving up on me every time I gave up on this study and on myself.

I would also like to extend my appreciation to Prof. Akiko Okabe and to Prof. Takashi Mino for their valuable comments during the development of this research.

Much appreciation is also due to the Asian Development Bank Japan Scholarship Program (ADB-JSP) for opening a window of opportunity by providing the financial support needed during the course of my academic stay in Japan.

Further extension of my gratefulness also goes towards all the members of Mino-Satoh Laboratory for their patience and support within and outside of the academia which were invaluable in making this study come into fruition.

I would also like to thank my family and friends who have been extraordinarily supportive of me, however difficult or odd I may be.

Finally, I would like to express my heartfelt appreciation to Kim for all aspects that apply.

TABLE OF CONTENTS

List of Tables and Figures

Abstract

The study explored the behavior of sewer self-purification processes focusing on lipid degradation. The discussion is divided into two parts starting with the critical review of related and relevant literature on wastewater treatment systems followed by the experimental evaluation of lipid degradation in the application of intermittent contact oxidation process (ICOP) for in-sewer purification.

The review identified regions that needed improvement in wastewater treatment and sanitation which included the rural and peri-urban areas of Southeast Asia. The dichotomy between centralised and decentralised wastewater treatment and management systems was discussed to identify which could best address the wastewater treatment and sanitation needs of the aforementioned region. Finally, it was identified that the key is the flexibility between centralised and decentralised systems. The flexibility could be addressed by the proper consideration of the collection system as part of the wastewater treatment process because it exists in both systems. The collection system can also potentially contribute to the removal of organic matter in wastewater.

Then, the behavior of the Intermittent Contact Oxidation Process (ICOP) was explored focusing on its capacity to degrade lipids for its in-sewer treatment applications. The ICOP is an attached growth process that uses biologically active sponge media fixed within a vessel. The fixed media is subjected to sewage flow intermittency resulting to the aerobic removal of organic pollutants in wastewater. The degradation rate of different lipid samples were explored in separate experiments incorporating the effect of sponge media headspace-gas exposure, the effect of initial oxygen concentration in the headspace-gas, and the effect of various nitrogen and phosphorous concentrations in the nutrient feed. To do so, three laboratory-scale air-tight pipe reactors were fabricated and operated with margarine, calcium oleate, and 5% methyl oleate in hexadecane as the carbon sources, respectively.

The results showed that the degradation rates found at normal oxygen concentrations having a range of 1.1 – 8.3 kg COD/($m^3 \cdot$ day) at 20 ± 1°C expressed per volume of sponge media is affected by wastewater flow intermittency where lipid degradation was decreased but sustained during prolonged periods without water flow. The degradation rates were also affected by substrate composition where increasing carbon chain length and saturation of the lipid substrate decreased degradation rates.

Process control options were also explored for the in-sewer degradation of lipids using ICOP. The effect of various nutrient concentrations in the nutrient feed was found to be negligible within the tested range. Further, the results indicated that increasing oxygen concentration positively affected degradation rate of lipids. The obtained findings provide understanding for the application of ICOP in collection systems.

CHAPTER 1

Introduction

1.1 Background of the Study

One of the challenges of providing clean water and sanitation for all is establishing a suitable wastewater treatment system that addresses the needs of rural and peri-urban areas of developing countries [1]. The solution should be appropriate for the place of application. For this, a decentralised approach is becoming a more preferred option [2]. Decentralised wastewater treatment systems are designed on an “as needed” basis and are customized to the need of the end users which favors its application in developing countries [3]. However, decentralised wastewater treatment may not be able to compete with the existing treatment capacity and technical competence exhibited by centralised systems [4]. To address this, an initial decentralised approach with provisions for centralisation may be advisable.

Decentralised wastewater treatment systems are associated with the onsite treatment of wastewater while a centralised system collects, transports, and treats wastewater far from the source or in an offsite manner. Both wastewater treatment systems invest on technology therefore, it is important to account for the reliability, efficiency, and flexibility of a treatment technology considering that it should endure factors like climate, geography, demography, and culture of the region of application. The technology needs to address concerns about affordability, appropriateness, and acceptability to the stakeholders involved [5]. Hence, a technology that can address all of these and give flexibility between centralised and decentralised wastewater treatment systems would be worth exploring.

A technology that exists in both centralised and decentralised systems is the collection system. It is thought that the collection system can be used as a part of the wastewater treatment process with its inherent capability to remove organic pollutants in wastewater through the process of sewer self-purification or in-sewer purification. Using the collection system as a part of the treatment process eases the transition between centralised and decentralised wastewater treatment systems allowing for the flexible treatment and management of wastewater.

To explore the capability of the collection system to treat wastewater, this study explored the Intermittent Contact Oxidation Process (ICOP) for its capability to degrade organic matter during its transportation through a sewer pipe. The ICOP uses a fixed sponge media to support biomass growth. The biomass growing on and within the sponge media is then intermittently exposed to sewage creating a cycle wherein at a high wastewater flow, substrate is supplied and at a low flow, media is exposed to air while retaining moisture within the sponge cavity. This allows the aerobic biological treatment of sewage.

The ICOP can be observed in the purification pipe technology which is an emerging technology that is proposed for the biological treatment of municipal wastewater [6]. The purification pipe technology builds on the inherent capability of the sewer pipe to remove organic pollutants through sewer self-purification. The self-purification is enhanced by modifying the pipe surface to promote biomass growth and retention – an essential factor in the biological removal of organic load and the similar mechanism used with ICOP [7 – 8]. However, the enhanced biomass growth means that there is a potential for clogging of the surface modification especially with known accumulation-forming substances like lipids present in sewage. This leaves a gap towards the application of the in-sewer purification technology.

Lipids – defined as fats, oils, greases, and fatty acids – constitute 10-80% of the total chemical oxygen demand in municipal sewage [9]. Lipids in sewage can exist in different forms depending on their physicochemical properties and environmental conditions. Lipids often form a hydrophobic layer on top of the water surface due to its lower density. This layer reduces oxygen mass transfer to the water phase [10]. It subsequently accumulates along the sewer pipe interior [11]. Previous studies have found that these accumulations exist either as calcium salts [12] or lipids layered with calcium salts both formed from the reaction of long-chain fatty acids (LCFA) and calcium leaching from concrete corrosion [13]. These lipid accumulations have been found to be biodegradable in simulated aerobic sewer conditions [14]. However, lipid accumulation and degradation behavior have not been extensively studied for attached growth processes applied in sewer systems.

1.2 Objectives of the Study

Intermittent contact oxidation is a process observed in the in-sewer purification pipe technology. The process builds on the inherent capability of the collection system to self-purify through the enhancement and retention of biomass growth. When this is applied to the collection system, it is thought to improve wastewater treatment and management in developing countries. This is because the collection system provides flexibility between centralised and decentralised wastewater treatment systems.

As mentioned, the intermittent contact oxidation relies on the enhancement and retention of biomass within the collection system. This is done through fixing a sponge media and exposing the media to intermittent sewage flow in order to remove organic pollutants. As such, there is an expected risk of clogging within the sponge media with known accumulation-forming substances like lipids present in sewage which can be detrimental to the performance of the collection system.

Under this narrative, the following questions are asked:

1. How does the use of the collection system provide flexibility between centralised and decentralised wastewater treatment systems?
2. If applied, how does the intermittent contact oxidation process behave with the threat of accumulated organic pollutants?
3. What operational controls can be explored to improve the performance of the intermittent contact oxidation process applied to in-sewer purification?

To address these questions, the general objective of this study is to explore the application of the ICOP for the degradation of lipids focusing on its in-sewer application.

The first specific objective of this study is to create an extensive review of literature about the existing situation between centralised and decentralised wastewater treatment systems. The discussion would clarify the current challenges occurring in both wastewater treatment systems and how in-sewer purification technology can address these challenges through providing a flexible technology that is utilized in both systems. The discussion would also extend towards the wastewater treatment and sanitation in the rural and peri-urban Southeast Asian region highlighting the immediate concerns and considerations with wastewater treatment.

The second specific objective of this study is to explore the capacity of the ICOP for the degradation of different lipid types. This can be done by monitoring the degradation rate of three different lipid substrates with flow intermittency. The substrates are limited to the following: margarine, calcium oleate, and 5% methyl oleate in hexadecane. These substrates represent various lipid types found in wastewater.

The final specific objective of this study is to explore process control options for the application of the ICOP for the in-sewer degradation of lipids. This can be explored by observing the degradation rate of different lipid substrates with the application of the following variables: various concentrations of ammonia, various concentrations of phosphorous, and various initial concentrations of headspace-gas oxygen concentration.

1.3 Manuscript Structure

This manuscript is divided into five chapters with the contents described as follows:

Chapter 1 profiles the general introduction of the study including the overview, the objectives, and the manuscript structure.

Chapter 2 presents the critical review of related literature pertaining to the status of wastewater treatment and management in the Southeast Asian region. The chapter synthesizes articles, reports, presentations, proceedings, and textbooks related to the development and application of the current wastewater treatment systems and the challenges relating to them.

Chapter 3 reviews the related literature on in-sewer purification discussing relevant biological processes and finally ending the narrative with the challenges associated with its application.

Chapter 4 describes the detailed methodology of the experiments conducted for the study. This section describes the experimental set-up and the succeeding three experiments executed which are defined separately.

Chapter 5 elaborates the results and relevant discussions for the study. The discussion focuses on the trends gathered from the experiments and discusses each separately.

Chapter 6 summarizes the findings leading to the conclusions and recommendations gathered from the results of the study.

CHAPTER 2

Wastewater Treatment and Management in Southeast Asia

2.1 Wastewater Treatment Approaches in Developing Countries

The global thrust towards eradicating poverty with supporting measurable, universally-agreed, and time-bound objectives was spearheaded by the Millennium Development Goals (MDG). Although it has achieved some improvement in eradicating poverty and disease [15], the provisions of the MDGs were expected to culminate in 2015. Hence, in the United Nations Conference on Sustainable Development held in Rio de Janeiro in 2012, the proposal for an extended and inclusive framework embodied by the Sustainable Development Goals (SDG) was inevitable. The thrust of the SDGs is the continuity of the goals established and achieved through the MDGs with the added consideration for sustainability [16]. Sustainability here means to provide, support, encourage, and manage something to meet the demands of the present and future generations [17].

One of the 17 SDGs established is to provide access to clean water and sanitation to everyone by the year 2030. The 2017 UN progress report on the SDGs cites that clean water and sanitation is available to two-thirds of the total world population. Achieving the 100% goal involves the attention to wastewater management focusing on providing appropriate strategies in the rural and peri-urban areas of developing countries [1]. From here, a review of the existing literature on the different wastewater treatment approaches and the challenges associated with the strategies and technology present in each will be discussed. The findings will be summarized and evaluated on which is the best-fit model for the wastewater treatment of rural and peri-urban areas of developing countries will be presented.

The reviewed literature for this chapter covers journal articles, country reports on wastewater treatment management in developing countries, proceedings from water environment conferences and symposiums, conference presentations on Southeast Asian water environment, text books specializing on decentralised wastewater management, textbooks specializing on wastewater management in developing countries, and textbooks on wastewater management and engineering. The keywords used for finding journal articles and conference proceedings include but are not limited to the following: Southeast Asia, wastewater treatment, decentralised wastewater treatment, centralised wastewater treatment, sewer systems.

2.1.1 Centralised and Decentralised Wastewater Treatment Systems

Wastewater treatment strategies discourses the dichotomy between centralisation and decentralisation with an interest for improving the situation for the rural and peri-urban regions of developing countries. In this regard, a discussion on which of the two would be the best-fit in the context of providing sanitation to these regions should be provided. The following section discusses the characteristics of centralised and decentralised wastewater treatment systems, the merits and demerits of each approach, and the perceived challenges of each in providing wastewater treatment and sanitation in rural and peri-urban communities of developing countries.

Centralised Wastewater Collection and Treatment Systems

Centralised wastewater collection and treatment (CWCT) systems focuses on the centrality of its operation where it traditionally collects, transports, and treats the settlement-generated wastewater away from the source (**Fig. 1**). CWCT starts with the installation of long pipes to create the collection or sewer system. This system transports the wastewater from the settlement to an "end-of-pipe" wastewater treatment facility where the wastewater is treated for safe discharge into the water environment [18].

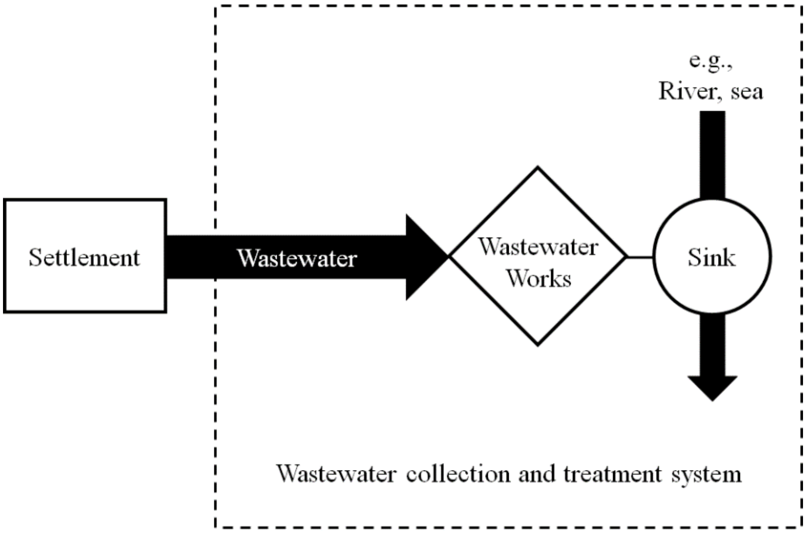


Fig. 1 Centralised system of wastewater transport and treatment [15].

There are merits and demerits for using CWCT systems. CWCT systems provide reliable and efficient wastewater treatment for both the consumer and the environment because the "end-of-pipe" treatment facility is operated by trained personnel [19 – 20]. This ensures that the treated wastewater is discharged to the water environment within acceptable specifications. However, the efficiency of CWCT systems starts from the collection system which comprises the majority of the capital costs [3, 17]. Depending on the scale, the installation of the collection system can also be taxing to the consumer as it requires excavation to lay-out and install the pipes [21]. After installation, due maintenance of the collection and treatment facility by trained personnel also compound on the operational cost of CWCT systems [22 – 23]. Finally, the failure to address population density also affects the overall performance of a CWCT system where an unperceived increase in population may lead to overcapacity of both the collection and treatment facility [24]. Conversely, a population decrease may also cause adverse effects like decreasing the profitability of constructing [25] and maintaining [26] the collection system.

Understanding the development of the collection system is also important in understanding CWCT systems. The evolution of the collection system and its integration to wastewater treatment typically proceed as follows:

1. The community first installed storm drains to address storm water transport and discharge. The storm drainages were eventually used to also collect and transport sanitary wastewater from households. The combined sewage were discharged to proximate water bodies without treatment which caused water pollution.

2. Main sewers, or sewers which intercept the storm drainages, were constructed to transport the combined sewage collected by the storm drains to divert its discharge from proximate water bodies into an “end-of-pipe” wastewater treatment facility. However, intercepting sewers as well as the “end-of-pipe” treatment facility have limited capacity in cases of heavy rainfall. As such, untreated wastewater is discharged to open water sinks in events called combined sewer overflow (CSO).

3. Alternatively, the existing storm drains are demolished and new sewers are constructed. Intercepting sewers and “end-of-pipe” treatment facilities also exist in this strategy. Similarly, CSO still persists.

These series of events led to the development of the combined sewer system which transports both sanitary wastewater and storm water in the same network [27]. As mentioned above, heavy rainfall can cause CSO [28]. Countering the health and environmental risks produced by CSOs led to the development of the separated sewer system which transports sewage and storm water separately [27].

A faulty collection system is preventive towards wastewater treatment in CWCT systems. This is because wastewater cannot be treated unless it is collected and transported to the "end-of-pipe" treatment facility as in the case of CSOs. However, the discussion on wastewater treatment often focuses only on "end-of-pipe" treatment facilities while putting less emphasis on the collection system.

In summary, CWCT systems provide efficient wastewater treatment and sanitation through the collection and treatment of wastewater in a professionally-controlled "end-of-pipe" wastewater treatment facility. The apparent disadvantage of CWCT systems is the financial and labor cost of its installation and operation where the collection system takes the bulk of the financial requirements. Further, the misconstrued view that the performance of CWCT systems is primarily reliant on "end-of-pipe" wastewater treatment facilities is problematic due to a large portion of CWCT systems being the collection system.

Decentralised Wastewater Treatment Systems

Decentralised wastewater treatment (DWT) systems treat wastewater onsite or near the source [20]. This means that there is a minimal use of the collection system. As such, DWT systems dedicate most of the capital cost to wastewater treatment technology installation [29]. Technology selection largely considers the needs of the region of application making DWT systems known for being installed on an "as-needed" basis [3].

DWT systems use components which are similar to the CWCT systems. The similarity begins with both systems needing the collection system, the treatment technology, the effluent disposal, and the management of biosolids [30]. Although both systems have the collection and end-of-pipe treatment systems, DWT uses a minimized form of both. The similarities between CWCT and DWT systems make differentiation in terms of scale or service correspondence (whether one-to-one or one-to-many) difficult [5]. Hence, the difference between the two systems are often discussed by their respective treatment and disposal behavior – whether onsite or offsite.

Considerable thought should be given in technological selection with an emphasis on appropriateness. Appropriateness can be gauged in whether a technology can address economic affordability, environmental sustainability, and social acceptability in the region of application [31]. Apart from technological appropriateness, the capacity of the end-user to operate the selected technology should also be gauged because the treatment performance of DWT systems relies on end-user maintenance. The technology should be simple enough to be maintained by non-professionals. If the DWT technology is too complex such that the maintenance is compromised, treatment performance would be compromised making DWT systems financially unsound for long-term investment [4].

Aside from choosing an appropriate technology, much thought must also be given as to what situation requires the application of DWT systems. The kinds of scenarios where applying DWT systems are acceptable have been discussed by Crites and Tchobanoglous [32] where the first thing that should be considered is whether a wastewater treatment system already exists within the region. This is followed by evaluating whether the system needs to be improved and whether the community can financially invest in CWCT systems. Further concerns involve the proximity of the community to existing centralised collection systems where rural communities are essentially exempted. According to these specifications, DWT systems should be chosen where funding and access to existing collection systems are insufficient.

Summarily, DWT systems have the advantage of being a flexible approach for wastewater treatment. The deficiency of DWT systems exists in its reliance on technology where investment and maintenance are evaluated on an “as-needed” basis which is largely based on end-user performance and evaluation. In terms of expansion, DWT systems which have minimal collection systems can be connected together to form a larger collection network. However, without an “end-of-pipe” wastewater treatment facility, the treatment capacity of DWT systems would still be dependent on the individual performance of the installed treatment technology.

CWCT vs. DWT for Application in Rural and Peri-urban Areas

There are plenty of issues in the discussion of wastewater treatment for rural and peri-urban regions of developing countries. Some of the issues already discussed include the financial capability and geographical proximity to existing wastewater treatment infrastructure of the concerned community. Small communities which are prevalent in both rural and peri-urban regions, have the disadvantage of being financially challenged [32 – 33]. Further, population density should also be considered. Hamid and Ujang [34] emphasizes the limits imposed by the lack of funding that low-population density communities have. It should also be considered that peri-urban communities located around urban centers are non-homogenous in terms of population and economy which makes neither wastewater treatment systems sufficient to address all community types [35]. Finally, problems also exist in the competence of the locality to handle and maintain the systems installed [4].

DWT systems are suggested to be the better option for the goal to provide clean water and sanitation for rural and peri-urban regions given that these systems are managed in a centralised manner [3, 5, 33, 36]. Management in a centralised manner means that the maintenance and operation of the decentralised treatment systems should be the responsibility of a technically trained organization. This is done to ensure that the effluent meets environmental standards by properly maintaining the treatment systems.

Proposing the use of DWT systems promises financial and technological flexibility in terms of technology selection and application however, the reliance of these systems on what is existing cannot fully address the treatment requirements of a given community. Conversely, the efficiency of CWCT systems cannot fully counter its high cost of installation and operation. However, the freedom of choosing what is appropriate for a community plays a key role towards achieving proper sanitation.

The discussion provided in this section revealed that CWCT and DWT systems, functioning on their own, cannot fully address the wastewater treatment and sanitation concerns of peri-urban and rural communities. Peri-urban communities, although still less populated compared to urban centers, can eventually grow and exceed the treatment capacity of installed onsite systems. Rural communities may not remain rural. Similarly, urban settlements may not remain urban. Although both CWCT and DWT systems can cater to large or small populations depending on the financial and technical restraints of the region [5], the treatment system and management practice employed should be fluid between the two systems. The dichotomy should also be discussed on a case-to-case basis in order to clarify what gaps exist and the best way to address them.

2.1.2 Conventional Wastewater Treatment and Management in Centralised and Decentralised Systems

In order to facilitate the understanding of the gaps that exist in providing sanitation for rural and peri-urban regions of developing countries through either CWCT or DWT approaches, it should be assumed that they are similar in the use of technology. The technologies that can be used for CWCT can also be used in DWT and vice versa. Thus, the discussion from hereon will be based on the proximity of said technology to the wastewater source. This section will identify cases where treatment technologies were applied, how they fit in CWCT or DWT approaches, and the challenges each technology faced in treating wastewater in their respective regions of application.

Individual Decentralised Treatment

Addressing personal hygiene and other sanitation events involve the use of onsite treatment technology [32]. Individual treatment systems may not necessarily produce wastewater as in the case of pit and composting latrines. However, discussing individual decentralised treatment technology starting with waste treatment is important in order to fully grasp the evolution of wastewater treatment.

The different types of household-generated wastewater can be divided into black and grey water. Households use onsite decentralised wastewater treatment technology to address the removal of organic matter coming from flushing toilets, baths, and kitchens among others. Black water is generated from flushing toilets while grey water is generated from kitchen and bath washings [4]. It should be noted that there are types of toilets which do not use water for flushing and therefore, do not generate black water.

One type of non-flushing toilet is the pit-latrine. Pit latrines collect and store human excreta in a pit or some form of receptacle placed underneath the toilet. Pit latrines do not require water to transport human excreta and source separation of solid and liquid discharges is not practiced. Organic pollutant removal is achieved by seepage into the surrounding soil [37]. An alternative version of the pit latrine is the composting pit latrine which transforms the organic matter into harmless, nutrient-rich organic matter. An example of this is the *sulabh shauchalaya* (affordable latrine) which offers low-maintenance sanitation as it uses a twin pit system which can be switched and covered upon reaching maximum capacity [38].

This brief summary of the pit latrine highlights the fact that human excreta is managed as solid waste.

The shift from pit latrines to flushing toilets came from the need to manage solid waste materials or biosolids. The onsite deterioration of human excreta creates foul smells and therefore creates discomfort within the community. Pests are also known to proliferate within the pit. Thus, with the introduction of the flushing toilet connected to onsite treatment technologies like septic tanks and *johkasou*, which will be explained later, odor and pests can be managed more easily.

Septic tanks remove organic matter in wastewater by sludge settling and anaerobic digestion [39]. Septic tanks treat mainly black water because they are connected to flushing toilets. As such, grey water is discharged into drainages without further treatment.

Johkasou technology in Japan was originally invented to treat black water so that flushing toilets can be used without being connected to the centralised sewer system. Later, another type of *johkasou* technology was invented so that grey water can be treated in addition to black water. The former type is called *tandoku-johkasou* or *minashi-johkasou*, the latter is called *gappei-johkasou* or simply *johkasou*. Hereafter, the term *johkasou* is used to mean the latter type, which treats both black and grey water. *Johkasou* aerobically removes organic pollutants and disinfects the effluent before discharging treated water into the environment [40]. Although *johkasou* systems can treat wastewater efficiently, electrical energy input is required for aeration thereby increasing its operation cost.

The challenges involved in using onsite decentralised wastewater treatment systems is the management of accumulated biosolids. In the case of the septic tank, it has exhibited a tendency to overflow because of untreated biosolids build-up [41]. Further, in some types of septic tanks, accumulated biosolids and sewage seep into the groundwater systems [42] causing health-related concerns upon the ingestion of the contaminated water [43]. *Johkasou* also faces challenges where biosolids accumulation becomes detrimental to its performance [40]. In both cases, end-user initiative to call on maintenance personnel is important. Another way to address biosolids management would be the introduction of a collection system. The collection system could then transport the biosolids to an “end-of-pipe” wastewater treatment facility.

Conventional Centralised Wastewater Treatment

Centralised wastewater treatment systems are comprised of the collection system and a treatment facility. Wastewater treatment starts with the collection and transportation of the wastewater to a required “end-of-pipe” treatment facility and ends with its discharge or reuse [17]. However, the collection system is often excluded from the discussion while the selection of the wastewater treatment process is emphasized.

A wide array of technology can be used for the “end-of-pipe” treatment facility starting from the conventional activated sludge process up to the newer membrane bioreactor [44]. The operation of the wastewater treatment facility is carried out by trained personnel and not by end-users. The personnel who handles treatment also handles the maintenance of the facility. This guarantees on-spec discharge of treated wastewater.

Challenges exist beyond the efficiency of the centralised wastewater treatment systems of which installation and operation are identified. The high capital costs of the collection system and treatment facility followed by the subsequent operation and maintenance cost usually prove to be too much for small communities [17, 25].

Challenges in Wastewater Treatment Applications in Developing Countries

Various articles suggest that centralised wastewater treatment facilities are not suitable for developing countries where the arguments hinge on financial and technical limitations [3 – 4, 31, 45 – 46]. The same articles also suggest that customized and high-rate decentralised treatment technology should be employed in order to compete with the performance of the centralised wastewater treatment facilities. These are the same arguments presented in the discussion on what is an appropriate wastewater treatment systems for rural and peri-urban communities. Hence, discussing and restating the qualities prominent in CWCT and DWT systems is important.

The previous sections about technology and management present that there is an abundance of choices for the application of either CWCT or DWT technology and management systems. **Table 1** summarizes the differences between the two systems and also illustrating the basic characteristics of cluster wastewater collection and treatment (CCT) systems.

Table 1. Properties of CWCT systems, DWT systems, and CCT systems.

	Proximity		Capital Cost		Treatment Efficiency		Population Density		Maintenance	
	Onsite	Offsite	High	Low	High	Low	High	Low	End-user	Trained Personnel
CWCT		✓	✓		✓		✓			✓
DWT	✓			✓		✓		✓	✓	
CCT	✓	✓	✓	✓	✓	✓	✓	✓		

CWCT and DWT technology and systems have different qualities which can be observed in small and cluster wastewater collection and treatment systems. Of the more prominent qualities, the flexibility of CCT systems in addressing both CWCT and DWT systems exist by its use of the collection system. Further discussion on CCT systems will be made in the next section.

Cluster Wastewater Collection and Treatment Systems

Cluster wastewater collection and treatment systems service more than one individual household and are usually installed with decentralised wastewater treatment technology linked through small collection systems [32, 34]. These systems exist in between CWCT and DWT systems as they can collect and treat wastewater onsite or offsite through the use of the collection system. The sewer systems are laid out with short, small diameter pipes embedded at shallow depths allowing lower demand for cost and labor in installation [4, 45]. Communities opt to choose CCT systems in cases where generated wastewater cannot be addressed by individual systems but are not financially and geographically capable of installing full-scale centralised treatment facilities [47].

Various types of wastewater treatment technology and strategies have been used and developed in CCT systems which include but are not limited to the following:

1. Natural treatment systems including constructed wetlands, lagoons, and waste stabilization ponds.
2. Biofilm processes including trickling filters and rotating biological contactors.

Natural wastewater treatment systems and biofilm processes take advantage of the physical, chemical, and biological processes produced from the interactions of microorganisms and the environment. The reactions occur in a natural rate through a manmade ecosystem thereby requiring less energy to maintain the treatment process [48].

Biofilm processes, including trickling filters and rotating biological reactors (RBC), differ from natural systems in that they do not mimic the natural environment but rather use biological processes to treat wastewater. Biofilm processes use microorganisms attached to media. Microorganisms then form biofilms which are then capable of organic pollutant removal in wastewater. Hence, the treatment capacity of these systems are dependent on the biofilm ecology whereas natural systems are dependent on natural ecology [44, 49].

Both the natural wastewater treatment systems and biofilm process produce less biosolids which reduces the maintenance cost [50]. However, the productions of biosolids can vary depending on the amount of organic pollutants being supplied into the system where a high pollutant concentration may produce more biosolids [51]. In this case, the biosolids and minerals accumulation may be greater than the degradation rate which means that maintenance frequency will increase for these systems.

CCT systems exhibit the finer points of both CWCT and DWT systems. All of the mentioned CCT systems have the following in common: have low energy input, have little requirement for maintenance when organic pollutant concentration is kept within operable range, and have low initial costs in installation [45]. Further, the technology can be modified for high-rate performance which can potentially compete with CWCT performance.

The key point in CCT is the use of the collection system as a conduit for expansion rather than simply for transport. In Bangkok, centralised systems were made on a city-wide scale by constructing sewer lines that intercepted storm drainages [52]. The use of drainages lessened construction costs because excavation and materials cost were minimized. This is also the case in Manila where lateral sewer lines were connected through existing septic tanks and then to small treatment facilities [53 – 54]. Small-scale CWCT systems in Japan are geared to connect to bigger centralised networks [55]. All of these scenarios were made possible through the collection system. Ergo, the proper regard and management of the collection system is worth exploring for providing wastewater treatment for rural and peri-urban areas of developing countries.

2.2 Wastewater Treatment in Southeast Asia

Understanding the problem and providing viable options in wastewater treatment and sanitation entails the identification of vulnerable regions. Included in the identified regions that need improvement on wastewater treatment and sanitation are the rural and peri-urban regions of Southeast Asia [1]. Southeast Asia is composed of 11 sovereign states including the members of the Association of Southeast Asian Nations (ASEAN) and East Timor. The region includes the countries Thailand, Vietnam, Cambodia, Lao People's Democratic Republic (PDR), Myanmar, Malaysia, Indonesia, Philippines, Singapore, Brunei, and East Timor. [56].

Although the rural and peri-urban regions of the Southeast Asian region are identified to need improvement in terms of providing wastewater treatment and sanitation, there are already existing strategies in place and further planning is being made to improve or expand the existing capacity [4]. Tackling the problem means to understand the existing scenario and derive suitable recommendations for its improvement. Here, the general wastewater treatment strategies are presented focusing on the developing countries of the Southeast Asian region. This will describe the wastewater treatment systems in place and the challenges identified in applying or achieving the mentioned wastewater treatment systems.

2.2.1 Wastewater Treatment Status in Southeast Asia

Understanding the current wastewater treatment scenario in the Southeast Asian region entails a brief background regarding its inception. Wastewater treatment and sanitation in the Southeast Asian region generally began with individual onsite wastewater treatment systems which included pour-flush latrines and septic tanks. The discharge from these individual systems often do not meet treatment standards in effluent quality which threatens the water environment upon discharge [57]. Improving these onsite wastewater treatment systems meant the introduction of an "end-of-pipe" treatment facility. The storm water drainages were turned into combined sewers during the course of directing household wastewater to the "end-of-pipe" wastewater treatment facility as mentioned previously. This led to the development of the current cluster and centralised wastewater treatment systems while maintaining the existing onsite wastewater treatment systems in the Southeast Asian region.

The present wastewater treatment strategies and the respective future plans for the Southeast Asian region are summarized per country in **Table 2.**

Table 2. Current wastewater treatment strategies used in the Southeast Asian region.

Country	**Present**			**Future**			**Remarks**	**Reference**
	DWT	CCT	CWCT	DWT	CCT	CWCT		
Cambodia	✓	✓				✓	*	[58 – 59]
Indonesia	✓		✓	✓		✓	*, **	[60]
Lao PDR	✓			✓	✓			[61 – 62]
Malaysia	✓		✓	✓		✓	*, **	[63 – 64]
Myanmar	✓	✓				✓	*	[65]
Philippines	✓	✓		✓		✓	*, **	[53 – 54, 66 – 67]
Thailand	✓		✓			✓	*	[63, 68 – 70]
Vietnam	✓	✓				✓		[71 – 72]

Remarks:

* - CWCT will be promoted in urban center

** - DWT will be promoted in rural areas

Indonesia, Lao PDR, Malaysia, and the Philippines integrate individual onsite decentralised wastewater treatment systems in the future plan of development together with developing CWCT systems. This choice of development wants to address rural communities where onsite systems are more financially sound [60]. However, the Philippines did not discriminate between rural and urban environments but rather fully integrated onsite systems in their development plan [73]. In the case of Lao PDR, DWT systems are preferred for both rural and urban environments citing easier involvement of stakeholders and lack of funding as the causes of preference.

On the other hand, some countries generally plan to apply CWCT systems in their urban centers and suburban region as in the cases of Thailand, and Vietnam. It should be noted that Thailand plans to continue minimally integrating onsite wastewater treatment systems in the rural areas. Cambodia and Myanmar also expressed the preference for CWCT systems but opted to limit its application to urban and tourism centers [58, 65].

The existing strategies to address wastewater treatment in the developing countries of Southeast Asia have been identified together with future plans of expansion. It is apparent that the development is mostly focused on urban centers – often with CWCT systems which are built upon the existing DWT systems. There are also prescribed plans for rural and peri-urban regions, most of which are limited to DWT systems such as septic tanks which have been discussed before as ill-adequate without proper "end-of-pipe" treatment. Although discussing the current scenario gave a broad view of the wastewater treatment scenario in Southeast Asia, it is now worth discussing the actual challenges this region faces in providing wastewater treatment and sanitation to rural and peri-urban regions.

2.2.2 Influences on Wastewater Treatment Technology and Management

The review of the wastewater treatment and management situation in Southeast Asian countries yielded the following considerations in choosing the wastewater treatment and management approach:

1. Availability of funding [60, 63, 65, 67, 69, 71, 74].
2. Engagement of the local community and national governance [58, 63, 67 – 68].
3. Technical expertise [61 – 63].
4. Availability of land [60, 67].
5. High population density [59, 75 – 77].
6. Availability of existing collection system [73, 78 – 79].

In the urban areas or developing countries, there is an initial preference for choosing low-tech, low-cost individual onsite wastewater treatment systems which stems from the following reasons: lack of available funding, lack of foresight in management during city planning, and gaps in engaging the local community [80]. However, these onsite systems were seen as inefficient and were needed to be overhauled. In the cases of Cambodia, Malaysia, and Thailand, governance saw through the centralised development of wastewater treatment systems which made it easier to execute and implement due to the provision of government funding [58, 63, 68]. In the Philippines, the government initiated the turn-over of water and wastewater treatment facilities to private sectors. This act has then improved the physical and management structures for wastewater treatment [73]. Without privatizing the water sector, the funding would have been difficult to acquire which would then hinder the development of wastewater treatment infrastructure [77].

The limited availability of land coupled with high population density also poses challenges towards wastewater treatment and management. The development of urban centers in developing countries came with the influx of migrant population seeking better economic opportunities and way of living. As population increased, so did real estate sales for settlements. This illustrates that as population density increases, land availability decreases. As housing and businesses expanded, so did the wastewater generation which became problematic due to the inefficiency of existing onsite treatment systems. The construction of wastewater treatment facilities is increasingly becoming more difficult to execute in highly populated areas particularly when there is no existing infrastructure like storm water drainages or lateral sewer lines installed [81].

The Southeast Asian region experiences abundant rainfall and the existence of storm drainages laid the foundation of improved wastewater treatment and sanitation. Thailand, using their version of canals called *klong* and the Philippines with their *estero,* have formed rudimentary combined sewer networks which transports wastewater away from the living environment and contributes to improved sanitation [82]. In Vietnam, although separate sewers have been introduced early, the collection system has now deteriorated making wastewater treatment a challenge [79]. On the other hand, interconnected drainages do not function properly in Lao PDR [83] which may result to health-related concerns rising from CSOs. In all of these mentioned examples, onsite wastewater treatment systems exist in the form of septic tanks and are deemed insufficient with or without rainfall events.

It is interesting that the dichotomy between DWT systems and CWCT systems are not explicitly mentioned in the reviewed literature except for Lao PDR which identified the need to decentralise. The wastewater treatment and management concerns were identified and expanded from the present scenario where above all concerns, sanitation must be provided.

Similarly, wastewater treatment concerns are continuously being improved through analyzing and expanding the present situation.

Although the aforementioned challenges were identified in the urban development of wastewater treatment, these can also be related to the peri-urban and rural areas of the Southeast Asian region. All of the six identified challenges are applicable in these areas excluding the challenges of land availability and high population density for the rural areas. Hence, a similar approach to start with DWT systems is advised to improve the wastewater treatment and sanitation condition due to the model's flexibility and appropriateness exhibited through a tailor-made and site-specific approach [49]. This can theoretically address the issues on funding, appropriateness, and technical simplicity. However, a provision towards CWCT and management should be considered as seen in the failure of poorly maintained DWT systems. Ultimately, the flexibility to address all of these is of primary importance to rural and peri-urban areas of the Southeast Asian region.

2.3 Implication of Collection Systems in Wastewater Treatment and Sanitation

The flexibility of wastewater treatment and management can be achieved through the proper consideration of the collection system. As described in the previous section, the existence of storm water drainages eased the development of urban wastewater treatment systems from onsite decentralised to centralised systems. In the non-existence of drainages, it would have been challenging to transition towards centralisation due to: (1) the financial burden of installing a new collection system, and (2) the socially taxing demand of construction on the surrounding community.

If it is not necessary or feasible for a community to centralise, the collection system is still important in managing water in a community. Urban and peri-urban areas are often covered in pavements which means that storm and grey water could not be easily absorbed by the soil. Flooding would occur without the means to transport water to a water sink (i.e. rivers). This can be detrimental to the living environment of Southeast Asia where septic tanks are wildly used because the resulting overflow would contain untreated sanitary wastewater.

The discussion on the collection system should be elevated to the same level as the discussion of the wastewater treatment technology and management used. The collection system is as much a part of the wastewater treatment process as the technology and management employed. This is because the failure of the collection system to collect and transport wastewater means the failure of the wastewater treatment process. Hence, proper attention towards the function of the collection system as a transport and connective medium that exists in both CWCT and DWT systems would provide flexibility needed for the provision of wastewater treatment and sanitation.

The proper consideration of collection systems provides one of the many directions that can help in the improvement of wastewater treatment and sanitation. It has been discussed that the collection system often already exists. Even when a community does not have a collection system, it is already described to be essential. Apart from its function of collecting and transporting wastewater, elevating the discussion further would delve into its potential to treat wastewater through a process called sewer self-purification. This process will be discussed in the next chapter.

CHAPTER 3

Processes, Applications, and Challenges for In-sewer Purification

3.1 Sewer Self-purification

An emerging technology that can be applied to both DWT and CWCT systems is the in-sewer purification technology. In-sewer purification has its basis on the self-purification characteristic of sewer pipes or the in-situ degradation of organic pollutant load – a concept that was pioneered by Pomeroy and Parkhurst [84]. Sewer systems have been investigated before for the capacity to degrade organic pollutants with the thought that sewers can be integrated as a pre-treatment process to a wastewater treatment plant design [7, 85]. Generally, self-purification allows sewers to act as biological reactors which can affect water quality through the aerobic and anaerobic transformations of organic matter [86]. It should be noted that anaerobic reactions are often preferred to be suppressed when regarding sewer processes.

3.1.1 Mechanism of Biological Organic Matter Transformation in Sewer Pipes

The biological removal of organic matter in sewer systems occurs with the aid of the microbial ecosystem that exists in biofilms [87]. **Figure 2** shows a sewer pipe cross section with the different phases where biofilms can grow. The sewer environment is generally composed of the bulk wastewater, the sediment phase, the moist unsubmerged inner wall, the biofilm, and the sewer atmosphere. Biochemical processes occur within these five regions and between phases including the gas-liquid interphase [88].

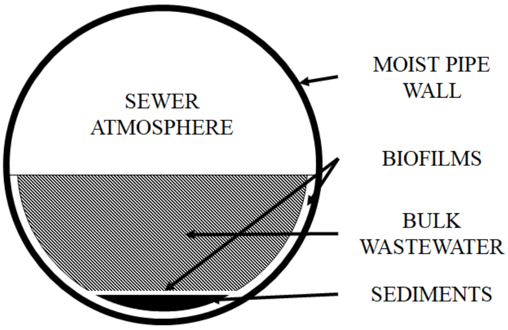


Fig. 2 Cross section of a sewer pipe highlighting different environments for microbial growth, i.e., bulk of wastewater, submerged biofilms, sediments, and moist, unsubmerged surfaces [87].

The biochemical processes that transform organic matter in the sewer environment, and specifically the sewer pipe, are complex. The reactions and transformations occur in separate regions, the majority of which happens within the bulk wastewater and between the wastewater and sediment interface. The more critical processes occur within the transformation of the particulate organic matter suspended in the bulk wastewater into dissolved organic matter and vice versa.

Organic matter present in sewers are divided into particulate and dissolved organic matter. Particulate organic matter is sequestered by the microorganisms present in the biofilm and are either hydrolyzed or fermented thereby becoming dissolved organic matter. The dissolved organic matter is secreted to the bulk water or used as substrate. The uptake of dissolved organic matter by microorganisms lead to growth and eventual sloughing off of the biofilm resulting to the increase of particulate organic matter in the bulk wastewater. Other processes present are adsorption, sedimentation, and resuspension of particulate organic matter. Adsorption and sedimentation occurs during low flow rate of wastewater where particles can settle within the biofilm causing it to be adsorbed or could settle at the bottom of the sewer causing sedimentation. Resuspension is observed during high flow rate where settled particles can be re-suspended. Volatile organic compounds (VOCs) were not considered in the overall scheme due to its negligible concentration in wastewater [89].

A simplified discussion on organic matter transformations in sewer pipes can be achieved by looking at the fundamental processes within the system. The removal of organic matter in sewer pipes are governed by biological and chemical processes involving oxidation-reduction reactions or redox reactions. The organic matter in sewage acts as the electron donor to an electron acceptor oxidizing the organic matter and reducing the acceptor. Redox reactions observed in sewer systems are described in **Fig. 3**.

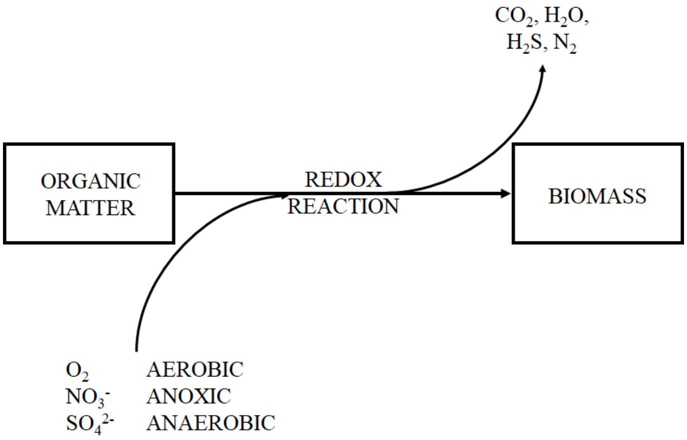


Fig. 3 Transformation of organic matter to biomass and oxidation products in the sewer environment [88].

The redox reaction that could proceed in the sewer environment can be predicted through the evaluation of the redox potential. A higher redox potential means a preference towards aerobic reactions and where the electron acceptor is oxygen (O_2). A lower redox potential means a preference towards anoxic or anaerobic reactions where the acceptors are nitrate (NO_3^-) and sulfate (SO_4^{2-}) respectively. Organic matter that undergoes redox reactions can either be oxidized to carbon dioxide (CO_2) or assimilated as biomass while the electron acceptors are reduced to H_2O, N_2, or H_2S. Among these redox reactions, the most energetically favorable is the aerobic reaction. Considering the dependence of sewer processes in the amount of biomass present, aerobic processes are more efficient in terms of energetic favorability and biomass activity. Literature suggests that for aerobic reactions, approximately half of the chemical oxygen demand (COD) is assimilated as biomass [88].

Process engineering of sewers are geared towards the prevention of anaerobic conditions from occurring. Anaerobic processes occur in several parts of the sewer including the bulk water phase, the sediments, and within the existing biofilm. Some of the processes involved in anaerobic sewer reactions are hydrolysis, fermentation, methanogenesis, and sulfate reduction. Although hydrolysis is important in the conversion of particulate substrates to soluble substrates, methanogenesis and sulfate reduction cause malodor and corrosion [88]. Anaerobic conditions causes malodor and concrete corrosion to persist within sewers. Further, anaerobic processes are slow to degrade organic matter causing accumulation of organic matter and concrete corrosion in sewer systems as evidenced by the laboratory study of He et al. [13 – 14].

Evaluating the organic matter removal capacity of the sewer pipe is important in discussing its potential application as a wastewater treatment technology. This can be done by monitoring the biological transformation of organic matter in the sewer pipe. Approaches previously applied by researchers for evaluating these changes are listed as follows:

1. Monitoring the concentration changes of total organic matter through analyzing biological oxygen demand (BOD), chemical oxygen demand (COD), or total organic carbon (TOC) [88, 90 – 93].
2. Monitoring the concentration changes of organic substrates or compounds like proteins, carbohydrates, or lipids [94].
3. Measuring the consumption of reactants including electron acceptors (i.e. oxygen, nitrate, and sulfate) or the formation of oxidation products [91, 95 – 96].
4. Evaluating enzyme activity by measuring potential hydrolytic respiration activity [97].

The questions that remain to be answered are what affects the self-purifying capacity of the sewer pipe and how engineering can control and enhance this capacity. Investigating the transformation of matter in the sewer pipe have given partial answers to these questions. Physical pipe modifications have been found to enhance the removal capacity of pipes in modelling studies. Using short pipes to treat wastewater is possible if biomass concentration can be maintained [98].

It has also been previously mentioned that aerobic degradation is more energetically favorable therefore the maintenance of the aerobic condition in pipe systems should be considered. The biofilm in sewer systems utilize dissolved oxygen (DO) in sewage [99]. This is governed by the transfer of oxygen from the sewer atmosphere to the flowing liquid phase [100]. Addition of external aeration equipment [7], incorporating ventilation, or creating drop structures in the sewer design [101] can assist in maintaining DO concentration in the bulk wastewater phase.

The organic matter removal performance of in-sewer purification is dependent on the active biomass present in the pipe [102]. Hence, discussing the sewer pipe as a biological reactor means focusing on the active biomass even though both mechanical and biological aspects coexist regarding its process control. Although the periodic addition of activated sludge have been proposed to retain biomass [85], other researchers have explored the modification of the inner pipe walls in order to promote biomass growth and retention [103 – 105]. This is the basis of the novel purification pipe system proposed by Shoji et al. [6].

3.1.2 Purification Pipe Technology

Sewer self-purification can be achieved through the promotion of microbial growth through utilizing an attached growth medium installed within a sewer pipe. This biologically active medium is then intermittently exposed to sewage and air through the wastewater flow cycles created during sewer pipe use. Substrate is supplied to microorganisms during sewage contact and is subsequently oxidized upon surface air exposure [106].

The biological oxidation induced by the intermittent contact of microorganisms to organic substrate and oxygen is comparable to the mechanism of the enhanced biological phosphate removal (EBPR) process in activated sludge systems. In the EBPR process, phosphate removal is achieved through cycling microorganisms between anaerobic and aerobic conditions to induce polyhydroxyalkanoate (PHA) and polyphosphate accumulation respectively. The purpose of the anaerobic phase is to select polyphosphate accumulating organisms (PAO). In the absence of effective electron acceptors like oxygen and nitrate for respiration, PAOs use the energy derived from the hydrolysis of polyphosphate to take up organic matter in sewage. Heterotrophic microorganisms other than PAOs cannot obtain energy to similarly take up organic matter in the absence of effective electron acceptors. The organic matter taken up by PAOs in the anaerobic phase is tentatively stored in their cells in the form of biopolymers like PHA. Afterwards, the aerobic phase induces polyphosphate accumulation while PHA is aerobically degraded as an energy source [107].

The EBPR process and sewer-self-purification are similar in the storage of organic matter in microbial cells. In sewer self-purification, the biofilm is subjected to surface aeration when the sewer pipe is not in use. Surface aeration promotes the aerobic oxidation of organic matter through the provision of molecular oxygen which in an effective electron acceptor. A pseudo-anaerobic cycle occurs when the sewer pipe is in use (e. g. rainfall event, flushing, washing). It is not fully anaerobic because of the dissolved oxygen contained in the bulk wastewater phase and because of the turbulence within the pipe which enhances oxygen dissolution [108]. During this pseudo-anaerobic cycle, microorganisms in the biofilm are submerged in wastewater where they can similarly take up and oxidize soluble organic matter.

The same intermittent contact to sewage and wastewater perceived in sewer self-purification is used by the novel purification pipe system to remove organic pollutants in wastewater. The purification pipe system shown in **Fig. 4** is an emerging technology that can be used for decentralised wastewater treatment. The double decked structure is achieved through the use of a separator. The upper deck is purposed for smooth transport of wastewater and the lower deck is designed to enhance sewer self-purification. Sewer self-purification is enhanced by biomass retention through the installation of polyethylene (PE) sponge media. Media air exposure during the low flow of wastewater maintains an aerobic environment for the biofilm allowing the oxidation of captured organic matter. The holes present in the structure create a drop where turbulence facilitates the dissolution of oxygen in the wastewater [6]. With this mechanism, the sewer pipe can aerobically degrade organic matter without the need for electricity [106].

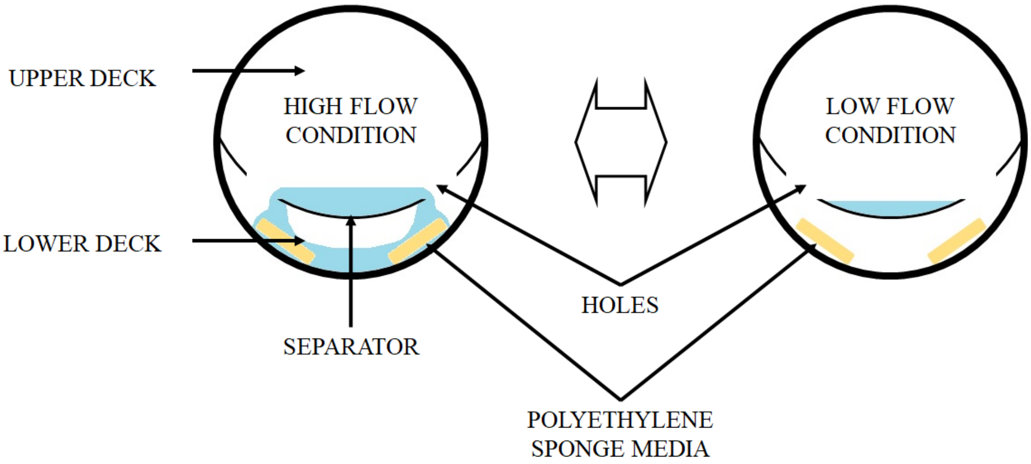


Fig. 4 Schematic diagram of the purifying pipe system for in-sewer treatment [6].

3.1.3 Challenges in Application

In-sewer purification technology fits both CWCT and DWT strategies because it can be applied in collection systems which are common to both. The potential of this technology to treat wastewater in rural and peri-urban regions of Southeast Asia can be seen in how it can address the perceived challenges for wastewater treatment. Using sewer pipes as biological reactors can lessen the pollutant load coming into wastewater treatment plants which can reduce its land footprint and initial cost. In-sewer purification can also address cases where there is no end-of-pipe or installed treatment facilities by lowering the oxygen demand in the receiving water body [7]. This technology also addresses climate concerns where tropical regions experiencing higher temperatures is thought to be synergistic towards the removal capacity of a sewer pipe [89 – 90].

Technological and social gaps should be addressed in order to pursue the application of in-sewer purification for wastewater treatment in Southeast Asia. With the characteristics presented, it is thought that the purification pipe technology is a flexible, affordable, and technologically simple therefore it can be applied in developing countries. Although it was demonstrated that the purification pipe can biologically remove organic matter [6], the technology is still in its developmental stage and proper consideration towards technology development should be prioritized. One of the technological concerns is the effect of accumulation-forming substances. The presence of accumulation-forming substances like lipids present in sewage poses the threat of clogging in the pipe especially if the accumulation rate is greater than the removal rate. Hence, investigating the lipid degradation behavior and capacity of sewer self-purification applying intermittent contact of sewage and surface aeration from, here named as the intermittent contact oxidation process (ICOP), should be explored.

3.2 Lipids in Wastewater

Lipids in sewage can exist in different forms depending on their physicochemical property and environmental conditions. Lipids are non-water soluble substances composed of a combination of fats, oils, greases, and free fatty acids. They are known to be aerobically degradable and are considered as part of the organic matter found in wastewater [109]. Lipids found in municipal wastewater are from food service establishments (FSE), food processing sites, and private domestic properties. The amount of lipids discharged into the collection system can be a function of population density as well as culinary culture [110].

3.2.1 Problems Associated with Lipid-containing Wastewater

Lipids encompass a significant portion of organic matter found in municipal wastewater making its removal behavior is significant in the wastewater treatment process. Lipids take up 10 – 80% of the total COD in municipal wastewater streams [9]. Although lipids are indeed biodegradable, several problems have been found with its discharge into the collection system as well as its end-of-pipe treatment.

Lipids are known to limit transfer of oxygen from the air to the water surface during aerobic treatment [111]. It readily forms a hydrophobic layer on top of the water surface due to its lower density. This layer reduces oxygen mass transfer to the water phase [10]. This limits the oxygen supply to the biofilm and reduces the ability of microorganisms to degrade lipids. In the sewer pipe, this decreased activity and continuous supply of organic matter causes lipids to accumulate along the sewer pipe interior [11] and also create sulfate-reducing conditions that produce corrosive sulfide [94].

Previous studies have found that lipid accumulations exist as the following: calcium salts [12], lipids absorbed in layers of calcium salts, and as calcium salts containing non-flushable materials [110]. These variations of calcium salts in sewers are formed from the reaction of long-chain fatty acids and calcium leaching from concrete corrosion [13]. These accumulations have caused overflow problems [12] and can only be removed by mechanical means [112]. The detrimental effect of lipids as suspended load was also found in activated sludge processes where it inhibited sludge settling thereby producing poor quality effluent in terms of particulate content [113].

Lipids also pose a potential problem in terms of compatibility with the ICOP and the purification pipe technology. It was found that the oxygen transfer to a fixed sponge media was decreased when the suspended solids (SS) content of the influent was increased [114]. This means that lipids existing as suspended load upon discharge can potentially accumulate and cause fouling in the purification pipe system. A study demonstrated that calcium palmitate is biodegradable in simulated aerobic and anoxic or nitrate-reducing sewer conditions [14]. Calcium palmitate has a similar composition to fatbergs which are the bulk of lipid accumulations found in sewer lines [12]. Although fatbergs are proven to be biodegradable in non-anaerobic sewer conditions, studies on in-sewer process control regarding lipids still remain lacking.

3.2.2 Biological Treatment of Lipid-containing Wastewater

Preventive measures exemplified by information campaigns have been done to alleviate the problems related to lipids and its accumulations in pipe system [111]. However, problems still persist in the events when lipids escape into the collection system. Addressing this means to review the mechanism of biological lipid degradation in order to find gaps relating to process control in sewer systems.

It has been mentioned that lipids can be biologically degraded in conditions where there is an oxygen source. The aerobic degradation of lipids, or its oxidative breakdown to carbon dioxide and uptake as biomass, proceeds through the beta-oxidation (β-oxidation) pathway in microorganisms shown in **Fig. 5**.

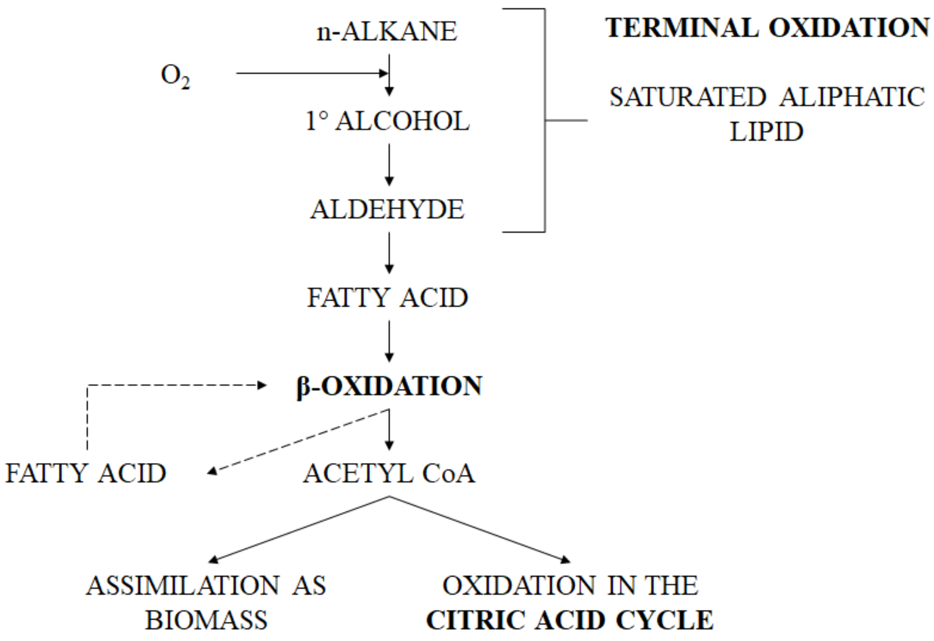


Fig. 5 Lipid catabolism through beta-oxidation [115].

Several types of lipids may enter the described metabolic pathway but for simplification, the catabolism or oxidative breakdown of saturated or unsaturated aliphatic fatty acids will be discussed as representatives of the lipid pool.

The catabolism of saturated aliphatic hydrocarbon start with the oxidation of its terminal carbon forming a primary alcohol. This reaction consumes oxygen because it is integrated into the aliphatic hydrocarbon in order to form alcohol. The terminal hydroxyl bond is further oxidized to an aldehyde and then finally a carboxylic acid forming a fatty acid of the same length as the original hydrocarbon. The saturated or unsaturated fatty acid then undergoes β-oxidation – a process where one cycle cleaves the original fatty acid producing a molecule of two-carbon acetyl CoA and a compound that is two carbon atoms shorter than the original fatty acid. The fatty acid product repeatedly undergoes β-oxidation until the final acetyl CoA is produced. Finally, acetyl CoA enters the citric acid cycle where it can be oxidized producing carbon dioxide [115]. In addition to saturation, the oddness or evenness of carbon number of the fatty acid substrate also affects degradation. Even-numbered fatty acids proceed as described above but for odd-numbered hydrocarbons, instead of producing a final molecule of two-carbon acetyl COA, three-carbon propionyl CoA is produced instead. In this case, propionyl CoA is converted to succinyl CoA before it is oxidized in the citric acid cycle [116]. The β-oxidation of lipids is an essential process for lipid metabolism in both aerobic and anoxic conditions where the difference only lies in the final electron acceptors where it is molecular oxygen in the former and nitrate in latter.

It should be noted that the discussion on lipid degradation is far more complex and the mechanism differs depending on the nature of the substrate. Further, the nature of the microbial consortium present in biological wastewater treatment affects the rate at which lipids are degraded.

The capability of microorganisms to degrade lipids has been studied before in both suspended and attached growth processes [44]. Previous studies on suspended growth systems introduced pure strains of screened microorganisms to a treatment system and the lipids were removed from the wastewater either by accumulation or by oxidation [117 – 118]. Other studies used microbial consortiums citing better removal results compared to pure strain studies suggesting the importance of microbial population [119 – 120]. However, the removal of lipids through suspended growth processes have resulted into poor effluent quality in terms of suspended solids [109].

Attached growth processes or fixed film processes have also been studied in terms of lipid degradation performance. Rotating biological contactors (RBC) have been used to treat palm oil mill effluent (POME) [121] and oily wastewater [122] with both studies resulting to reduced suspended solids in the effluent. El-masry et al. [123] studied a sand biofilm system inoculated with isolated strains of lipid-degrading bacteria. Their discussion highlighted the efficiency of the biofilm in removing fats, oil, and greases (FOG). More relevant to the discussion of the use of sponges and its application to sewer systems is the study conducted by Wan et al. [124] where soybean oil was successfully treated by *Pseudomonas aeruginosa* fixed on polyurethane foam (PUF). These studies showed the viability of attached growth processes in treating lipid load.

3.2.3 In-sewer Studies on Lipid Degradation

Lipid degradation has been studied before in the context of sewer systems. He et al. [14] have investigated the biodegradation of calcium salts in sewer-relevant redox environment which were: aerobic, nitrate-reducing, sulfate-reducing, and methanogenic conditions. Aerobic and nitrate-reducing conditions were demonstrated to degrade calcium salts with the aerobic condition being the more preferred condition. The results of this study highlight the importance of maintaining an aerobic environment in sewers. The study conducted by Raunkjær et al. [89] analyzed the removal of lipids focusing on the effect of transportation along a sewer pipe but produced inconclusive results.

Although efforts have been dedicated towards the end-of-pipe treatment of lipids, very few have explored lipid removal in the sewer pipe. It has been previously discussed that attached growth processes in sewer pipe systems can transform and remove organic pollutants in wastewater. Studies have also demonstrated that porous media can enhance biological treatment of wastewater by the retention of microorganisms [103 – 104, 125 – 126]. However, lipid degradation behavior have not been extensively studied for attached growth processes applied in sewer systems. The threat of fouling, among other concerns, remains relevant. This leaves an evidential gap in applying the ICOP and the purification pipe technology for the in-sewer treatment of organic load.

CHAPTER 4

Materials and Methods

4.1 Operation of an Air-tight Pipe Reactor

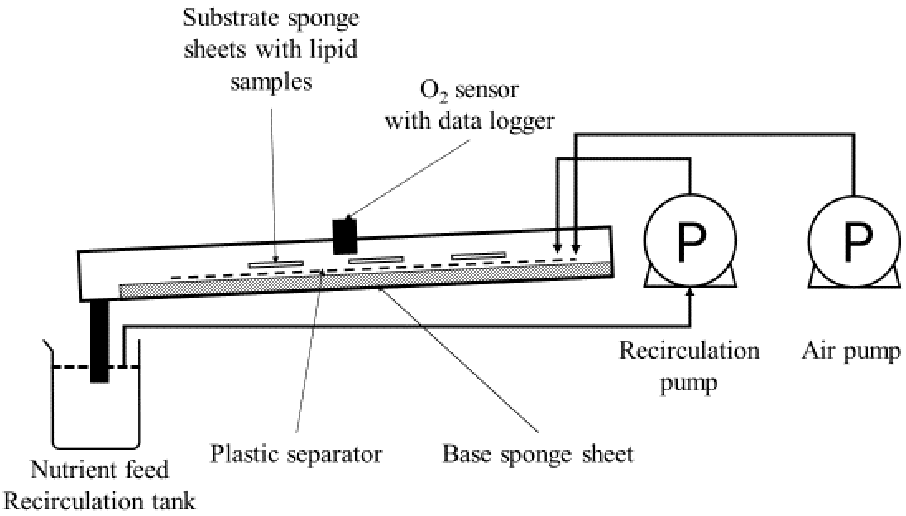
The following section describes the setup and operation of air-tight pipe reactors to investigate the degradation rate of lipid substrates. This section further describes the inoculation procedure used and the general method for the degradation rate estimation by monitoring headspace-gas oxygen concentration.

4.1.1 Reactor Setup

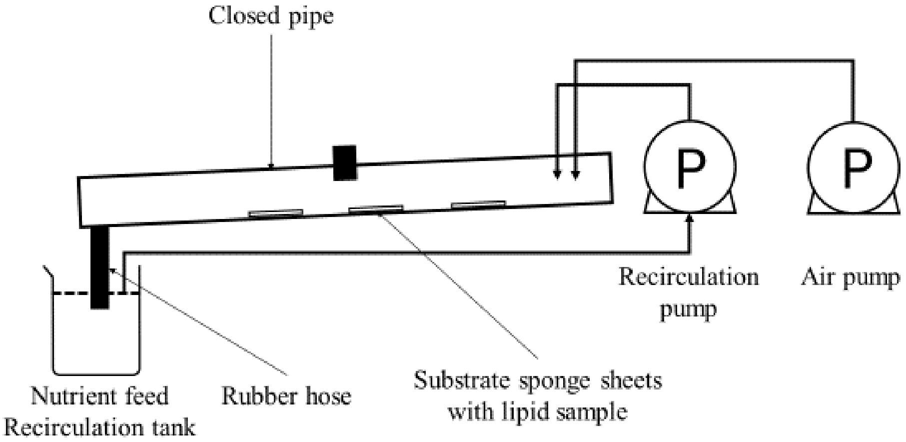
Three lab-scale air-tight pipe reactors, each consisting of a rectangular pipe, an oxygen sensor, a recirculation tank, recirculation pump, and an air pump were manufactured (**Fig. 6a**). Each pipe was fabricated with 0.5 cm thick transparent polyvinylchloride plastic plates. The dimensions of each reactor were 50 cm long, 7 cm width, and 5 cm depth with a total working volume of 1.75 L. The reactors were fitted with rubber hoses with an internal diameter of 15 mm and a length of 15 cm at the discharge side. Each reactor was made air-tight by fitting the sensor signal cable with rubber plugs, and fully submerging the outlet hose in nutrient feed contained in the recirculation tank. An oxygen gas sensor (ME2-O2-φ20, Winsen Electronics Technology, Zhengzhou, China) was installed inside each reactor to observe the oxygen concentration in the headspace-gas. The sensors were connected to a data logger compatible to an Arduino Uno board. The data logger collected sensor data every 1 minute.

Each of the recirculation tank had a working volume of 1 L and had an open structure. The recirculation pump cycled nutrient feed at set intervals. The recirculation pumps had a flow rate of 130 ml/min, and during recirculation pump operation of 5 minutes, approximately 650 ml of nutrient feed was cycled into each reactor. The air pumps were operated as experimentally needed for 2 minutes and had a maximum capacity of 5 L/min.

In each reactor, a base sponge sheet (1 cm depth, 7 cm width, and 40 cm long) and three polyethylene substrate sponge sheets (0.3 cm depth, 3.5 cm width, and 7 cm long) were fixed for inoculation (**Fig. 6a**). The nutrient feed solution used for inoculation contained per liter of tap water: KCl 73.3 mg, $CaCl_2 \cdot 2H_2O$ 44 mg, NH_4Cl 166.7 mg, $MgSO_4 \cdot 7H_2O$ 36.7 mg, and K_2HPO_4 24 mg. After inoculation, the base sponge sheet was removed and the substrate sponge sheets were retained for the next part of the study (**Fig. 6b**).



(a) Schematic diagram for inoculation of substrate sponge sheets



(b) Operational schematic diagram for air-tight rectangular pipe

Fig. 6 Schematic diagram of experimental setup.

4.1.2 Inoculating Conditions for Substrate Sponge Sheets

To inoculate microorganism to the substrate sponge sheets, fresh substrate sponge sheets were loaded with their respective lipid substrates and incubated with the base sponge sheet. The base sponge had been inoculated with return sludge from a municipal wastewater treatment plant. Prior to inoculation, 1 g of margarine (2.43 g COD), calcium oleate (2.74 g COD), or 5% methyl oleate in hexadecane (2.79 g COD) were applied to each of the substrate sponge sheet. The COD values were determined using a kit (High Range COD Digestion Vial, Hach, USA). The loaded substrate sponge sheets were fixed on top of the base sponge with a plastic separator placed in between the base and substrate sponge sheets to avoid the transfer of lipid substrates (**Fig. 7b**). Each reactor contained 3 substrate sponge sheets giving a total of 3 g of substrate. 650 ml of nutrient medium was repeatedly supplied for 5 minutes every 25 minutes. The nutrient medium was replaced every 2 days.

The setup was operated in an air-conditioned room maintained at 20±1°C. The base sponge was removed from the rectangular pipe reactor after 7 days when appreciable biofilm growth on the substrate sponge was observed. The inoculated substrate sponge sheets remained in the reactor for the experiments.

4.1.3 Degradation Rate Estimation

The lipid degradation rate was estimated from the slope of the change of the oxygen concentration with time. The slope was evaluated within each recirculation pattern applied. Since the slope would have a unit of % O_2 per unit time, the mass of oxygen consumed per unit time was computed as follows:

$$\frac{mass\ O_2}{time} = slope \times \frac{\rho_{oxygen,20°C} \times V_{reactor}}{100}$$

Where:
$mass\ O_2$: mass of oxygen
$slope$: slope of oxygen reduction ($\frac{\%O_2}{time}$)
$\rho_{oxygen,20°C}$: density of oxygen at 100% oxygen at 20°C, 1 atm, 1.33 g/L
$V_{reactor}$: void volume in the reactor, 1.75 L

The change in the mass of oxygen per unit time was taken as the mass of oxygen consumed for each reactor. This was taken directly as the mass of lipid COD mineralized by aerobic metabolism. The lipid degradation rate was expressed as the mass of COD oxidized per total volume or area of substrate sponge media per day.

4.2 Effect of Media Headspace-gas Exposure on Lipid Degradation Rate

After the inoculation of the substrate sponges, the effect of media headspace-gas exposure was explored by changing the operation of the recirculation pump. The recirculation pump was operated as follows: 5 minutes operation every 0, 25, 55, 115, 235, and 475 minutes. Here, 0 minutes recirculation pump operation means continuous flow operation. Recirculation patterns were changed at 8 hour intervals. The air pump refilled the reactors with outside air for 2 minutes when recirculation patterns were changed.

4.3 Effect of Initial Oxygen Concentration in the Headspace-gas

The effect of oxygen concentration in headspace-gas was tested following the effect of media headspace-gas exposure. The following initial oxygen concentrations were tested: 15, 20, and 25 $\%O_2$. All three conditions were observed with the following recirculation patterns applied: 5 minutes operation every 0, 25, 55, and 115 minutes. Oxygen or nitrogen gas was injected into each reactor to increase or decrease oxygen concentration. The change in oxygen concentration was observed at 2 hour intervals for each recirculation pattern. The reactors were flushed for 2 minutes with outside air before changing oxygen concentrations. The nutrient feed solution contained per liter of tap water: KCl 73.3 mg, $CaCl_2 \cdot 2H_2O$ 44 mg, NH_4Cl 166.7 mg, $MgSO_4 \cdot 7H_2O$ 36.7 mg, and K_2HPO_4 24 mg.

4.4 Effect of Various Nutrient Concentrations in the Nutrient Feed

Two separate substrate sponge sheets, identified as set P and set N, were inoculated to explore the effect of various nutrient concentrations in the nutrient feed. Six preparations of nutrient feed was loaded into the reactor successively. Each preparation set had the nutrient concentrations described in **Table 1**. For preparations P1, P2, and P3, the concentration of K_2HPO_4 was varied. For N1, N2, and N3, the concentrations of KCl, $CaCl_2 \cdot 2H_2O$, NH_4Cl 1, and $MgSO_4 \cdot 7H_2O$ were varied. The nutrient feed preparations were supplied by operating the recirculation pump as follows: 5 minutes operation every 235, 475, 0, 55, 115, and 25 minutes. Recirculation patterns were changed at 8 hour intervals. The air pump refilled the reactors with outside air for 2 minutes when recirculation patterns were changed.

Table 3. Concentration of nutrients supplied per batch run.*

Set	KCl	$CaCl_2 \cdot 2H_2O$	$MgSO_4 \cdot 7H_2O$	NH_4Cl	K_2HPO_4
P1	73.3	44	36.7	166.7	12
P2	73.3	44	36.7	166.7	48
P3	73.3	44	36.7	166.7	96
N1	36.7	22	18.4	83.4	24
N2	146.6	88	73.4	333.4	24
N3	293.2	176	146.8	666.8	24

* expressed in mg/L of nutrient feed

CHAPTER 5

Results and Discussion

5.1 Effect of Media Headspace-gas Exposure

The section describes the effect of various extents of media headspace-gas exposure on lipid degradation rate. The discussion is divided into four sections highlighting the theoretical background explaining the results gathered for the experiment.

5.1.1 Degradation Rate Estimation

The oxygen concentration change in each reactor was monitored and plotted against time as shown in **Fig. 7**. The lipid degradation rate expressed as lipid COD degradation rate was estimated from the linear slope gathered from the middle 6 hours of each recirculation pattern; indicated by double-headed arrows in **Fig. 7**. The slope of the oxygen consumption data was taken as the lipid COD degradation rate.

Oxygen concentration in the headspace gas data showed a linear decrease for all substrates. As previously discussed, lipid degradation consumes oxygen thereby decreasing the oxygen concentration in the reactor. This decrease corresponds to the lipid COD oxidized to carbon dioxide and water. In the rate estimation, several causes of oxygen depletion might occur like nitrification or microbial autolysis. Nitrification was thought to be negligible due to the minimal formation of both nitrite and nitrate in the nutrient feed (data not shown). Microbial autolysis was also thought to be negligible because the carbon source was in excess. Given that the only source of COD for the system was the applied lipid substrate, and nitrification was negligible, the estimated mass of oxygen consumed per reactor was taken as the mass of lipid oxidized as COD.

Soil respiration studies and this study have a similar approach in monitoring respiration activity. Soil respiration is usually observed by monitoring the gas concentration change in an isolated soil plot in-situ. This is done by installing gas sensors in the form of detectors or soda lime. The former commonly monitors the evolution of CO_2 or the depletion of O_2 using specific detectors [127]. On the other hand, soda lime method is a gravimetric approach to measure the amount of CO_2 evolved [128]. In both cases, gases are indicative of respiration.

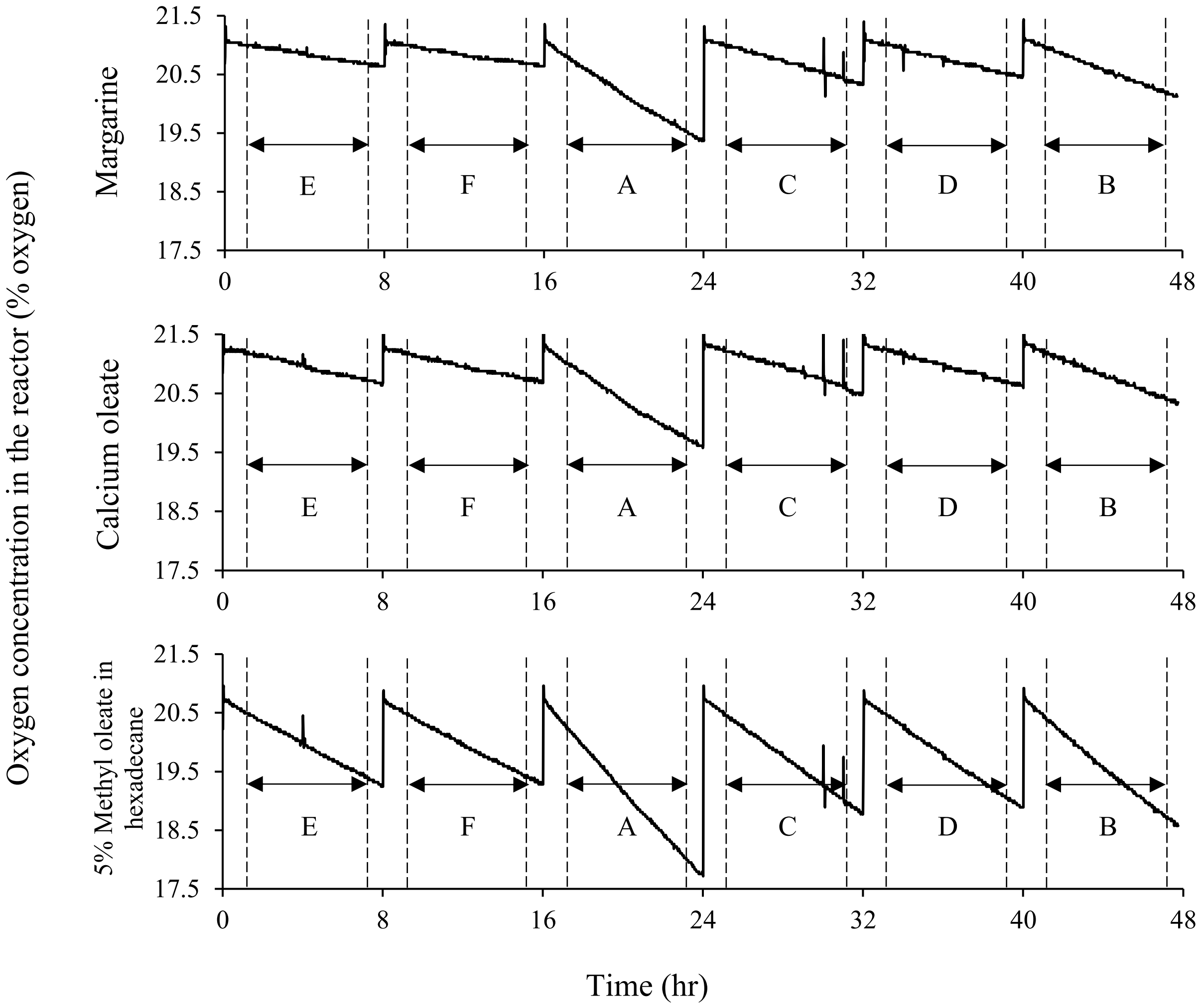


Fig. 7 Oxygen concentration change per applied recirculation pattern for margarine (M), calcium oleate (CO), and 5% methyl oleate in hexadecane (5% MO-HD). (A) Continuous flow, (B) flow every 25 minutes, (C) flow every 55 minutes, (D) flow every 115 minutes, (E) flow every 235 minutes, and (F) flow every 475 minutes.

5.1.2 Degradation Rate with Various Extents of Media Headspace-gas Exposure

The degradation rates of the different substrates were estimated and plotted against various extents of media headspace-gas exposure time (**Fig. 8**). The volumetric degradation rate ranges were: 1.3 – 5.3 kg COD/(m^3 · day) for margarine, 1.4 – 5.5 kg COD/(m^3 · day) for calcium oleate, and 4.2 – 9.2 kg COD/(m^3 · day) for 5% methyl oleate in hexadecane. Expressed in areal degradation rates, the ranges were: 0.4 – 1.6 g COD/(m^2 · day) for margarine, 0.4 – 1.6 g COD/(m^2 · day) for calcium oleate, and 1.2 – 2.8 g COD/(m^2 · day) for 5% methyl oleate in hexadecane.

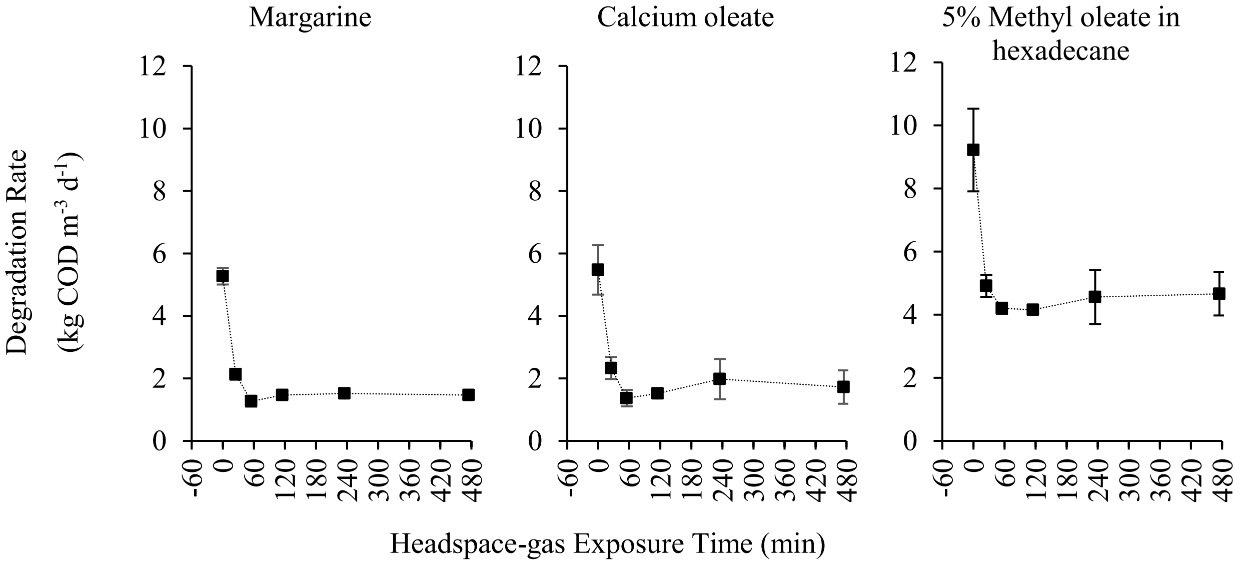


Fig. 8 Degradation rate change of various lipids with various extents without wastewater flow (n = 3 for all points, except for 235 minutes headspace-gas exposure time where n = 2).

The rate profiles showed a consistent trend for all substrates where extended periods without water flow decreased degradation rate. The trend was common among the tested lipid substrates. Considering oxygen dissolution in the recirculation tank, the rates provided may be underestimated and should be a bit higher than the calculated values. Further observation showed that there was sustained significant degradation after media headspace-gas exposure longer than 1 hour. The following percentages were estimated from the maximum degradation rates: 24% for margarine, 25% for calcium oleate, and 46% for 5% methyl oleate in hexadecane. From here, these questions will be answered: why was degradation enhanced with shorter media headspace-gas exposure, and why was degradation sustained with extended media headspace-gas exposure.

The first question can be answered by the enhancement of soluble substrate mass transfer with water flow. Mass transfer of oxygen occurs on a water surface layer where molecular diffusion dominates the mass transfer of soluble substrates [129]. With water flow, the dissolution of oxygen from the headspace-gas is enhanced because the layer experiencing surface aeration is replaced before solute saturation is reached.

Conversely, without water flow, the transport of soluble substrates proceeds only through slow molecular diffusion. In the case of oxygen dissolution, the oxygen gradient was obtained by first assuming that the top layer is saturated with oxygen at 20 – 21 °C (approx. 9 mg/L) and fully depleted at the bottom (0 mg/L). Since the sponge thickness was 3 mm, the resulting oxygen gradient when the surface concentration is divided by the thickness would be approximately 2.7 mg/ (L · mm). The oxygen flux was calculated by multiplying the oxygen gradient with the estimated diffusion coefficient of oxygen at 20°C (approx. 2 x 10^{-9} m^2/s). Under this condition, the oxygen flux is calculated to be about 0.5 g/(m^2 · day). The experimental results for the areal oxygen consumption rate that was in the range of 0.4 – 1.2 g/(m^2 · day), was close but a bit higher than the calculated value.

The lower oxygen consumption rate can also be attributed to the biofilm structure. The system used attached growth or biofilm processes to degrade organic load. Biofilms, including those found in sewers, are heterogeneous [130 – 131] meaning that the distributions of components are non-uniform. The mass transfer of oxygen within the biofilm is also affected by its tortuosity (property of having non-uniform surface structures) and permeability. The permeability of the biofilm to oxygen and other soluble organic matter is thought to decrease as depth increases suggesting less porosity at the bottom resulting to a decrease in mass transfer [131].

Another possible mechanism for the sustained but decreased degradation is the retention of water by the sponge media. Oxygen mass transfer traditionally relies on three factors which are: liquid mass transfer coefficient (k_L), surface area (α), and solute concentration pertaining to oxygen in the headspace-gas [99]. If the water that flows through the sponge media is treated as a moving film then the surface area available for oxygen mass transfer to the biofilm is dictated by the area of the film. The sponge media containing the biofilm would gradually lose water and mass transfer surface area by either dewatering or evaporation without water flow. The resulting water loss would then inhibit the DO supply to the biofilm. However, the expected impact is less pronounced as described previously by the degradation rates observed with headspace-gas exposure longer than 1 hr. It can be inferred that the presence of the sponge media may be affecting degradation rate at long extents of media headspace-gas exposure by facilitating oxygen mass transfer to the biofilm through water retention. However, the thickness of the sponge used for this study was only 0.3 cm and the effect of sponge thickness on water retention and oxygen transfer should be carefully explored.

The function of the sponge media in facilitating mass transfer to the biofilm is supported by the findings of Uemura et al. [114] where they explored the volumetric oxygen transfer coefficient ($k_L\alpha$) of a down-flow hanging sponge (DHS) system utilizing sponge media. They found that $k_L\alpha$ of a system carrying sponge media was higher than other attached growth processes which do not. The reason lies within its enhancement of surface area which was previously mentioned as a dimension required in oxygen mass transfer to the biofilm.

The observed rates highlight the potential of ICOP for its treatment of lipid load within transport pipes. It is projected that upon use, a 1 m transport pipe with an inner diameter of 20 cm installed with sponge media (1 cm thick, 20 cm wide, 1 m long) incorporating ICOP is expected to treat 2.6 – 18.4 g COD coming from lipids in municipal wastewater per day. Tentatively, a thickness of 1 cm can be used because it is assumed that lipids will accumulate and degrade on the sponge surface where it can be intermittently exposed to headspace-gas. It should be noted that optimizing sponge placement as well as the physical characterization of the media still needs to be explored.

Summarily, these estimations gave relevant information on the performance of ICOP with accumulation-forming substances like lipids. It is expected that with its application, accumulation may occur on and within the sponge media which could cause fouling. However, lipids and other organic load may be degraded within the given performance range because of the observed degradation with or without water flow.

5.1.3 Comparison to Other Lipid Degradation Studies

Comparing the lipid degradation rates of similar attached growth wastewater treatment systems is relevant to gauge how well a new technology performs. Of the attached growth systems investigated for lipid degradation, the rotating biological contactor (RBC) is decided to be the nearest comparison to the air-tight pipe reactor used for this study. Tyagi et al. [125] reviewed several studies which used RBCs to treat lipid-containing wastewater. The areal lipid degradation rates found for these studies were in the range of 1.0 – 2.9 $g/(m^2 \cdot day)$ which was higher compared to the 0.4 – 1.2 $g/(m^2 \cdot day)$ performance of the air-tight pipe reactor.

A direct comparison between the reported lipid degradation rates and the ones found in literature is difficult to establish. The RBCs investigated for lipid degradation show similarities to the air-tight pipe reactor where the systems used attached growth which experience intermittent surface aeration to degrade lipids. However, while the media in the air-tight reactor is static, the media used in RBCs rotates. The rotating motion is thought to facilitate lipid degradation rates because it increases the surface area of the lipids adsorbed on the disk surface which then enhances oxygen mass transfer relevant to the aerobic degradation of lipids [125].

5.1.4 Effect of lipid Composition on Degradation rate

Different substrates were tested to explore the capacity of ICOP to degrade lipid load. The differences in the observed rates between substrates could be affected by their physicochemical properties where stability, chain length, and unsaturation dictate the biodegradability of the lipid source. The biodegradability of lipids is affected by its solubility in the water phase [132]. Considering this, lipids with longer chain length and higher degrees of unsaturation were projected to be more difficult to degrade because these properties decrease lipid solubility in water and its transfer to the biofilm [133]. To confirm this point, the general hydrocarbon length and hydrocarbon saturation profile of each lipid substrate was compared as seen in **Fig. 9**.

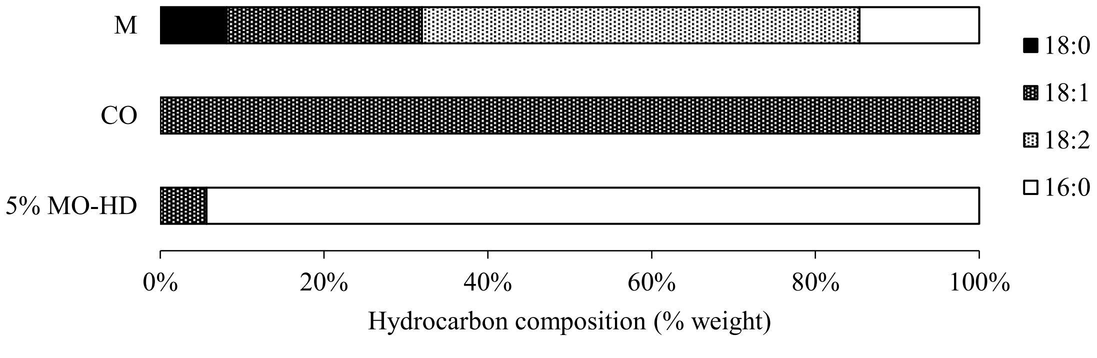


Fig. 9 Lipid substrate hydrocarbon chain saturation profile (M – margarine, CO – calcium oleate, 5% MO – HD – 5% methyl oleate in hexadecane).

It was previously illustrated that the M and CO samples had similar degradation rates. The similarity can be attributed to both substrates being composed of mostly C18 hydrocarbon species. The slight difference where CO degraded faster can also be explained by the degree of saturation of the C18 species present. However, it could not be concluded for both samples because the margarine sample also contained C16 species. For the 5% MO-HD sample contained 95% hexadecane, it was inferred and confirmed that the sample would degrade the fastest out of all the tested substrates because of its high content of saturated C16 hydrocarbon. Judging from the results, a prediction of degradation rates can be qualitatively estimated. Still, a fair comparison for the degradation mechanism cannot be solely attributed to the substrate properties. The biofilm population dynamics is also a major component in considering the lipid degradation mechanism and what affects it.

5.2 Effect of Initial Oxygen Concentration in the Headspace-gas

The degradation rates of various lipid samples were estimated from the slope of the 2 h evaluation under different initial oxygen concentrations in the headspace-gas (**Fig. 10**). There were two different trends that could be seen from the figure. First, there was a general increase in degradation rate with increasing headspace-gas oxygen concentration. Second, there was a general decrease in degradation rate with increasing duration of media exposure under various initial headspace-gas oxygen concentrations. The second result is consistent with the trend found in the previous section. The results highlighted that control of oxygen concentration in the gas phase is relevant in enhancing biofilm activity. In terms of operational control for the in-sewer application of ICOP, maintaining headspace oxygen concentration at normal saturation is enough to give a reliable degradation performance.

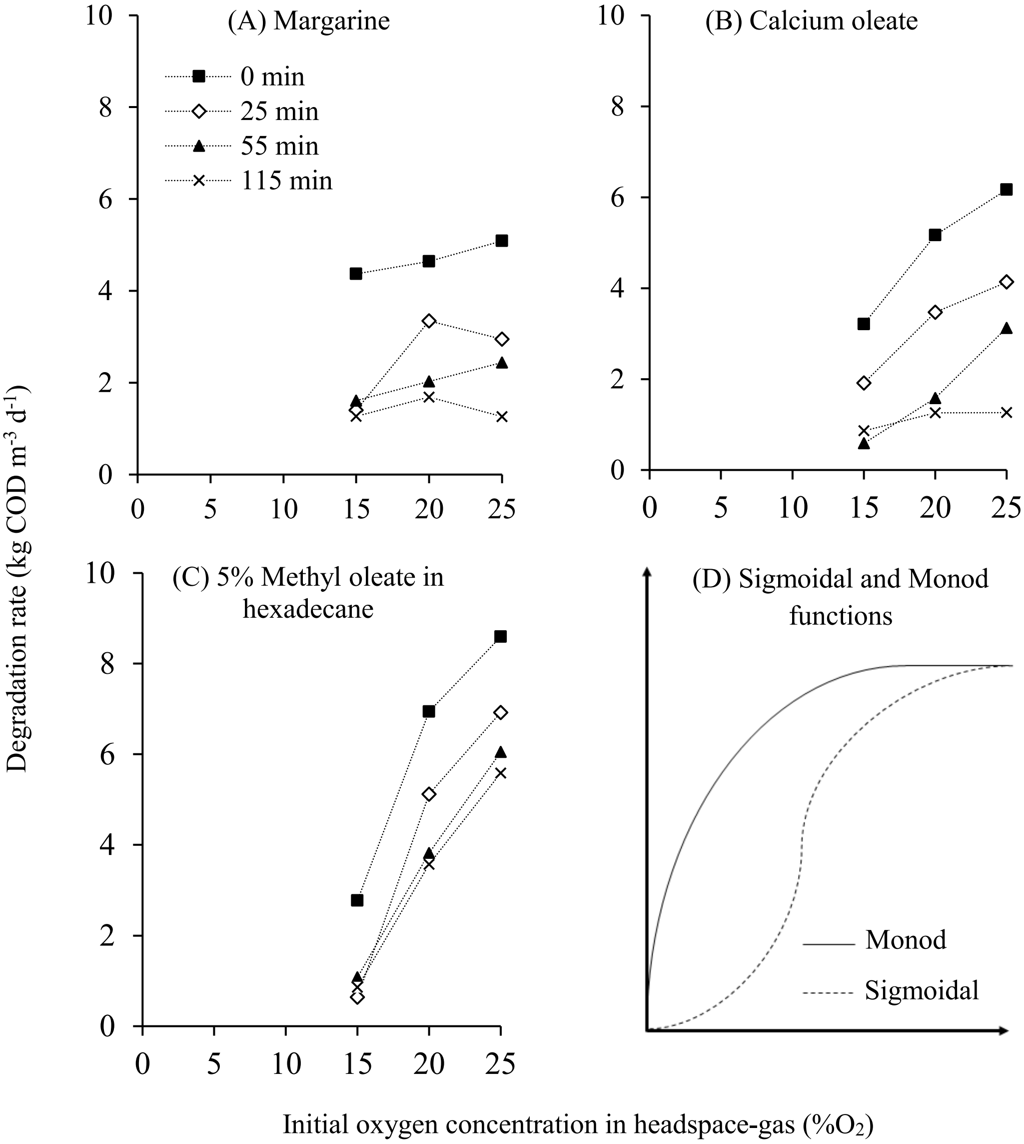


Fig. 10 Change of degradation rate with oxygen concentration under various extents of media headspace-gas exposure.

The kinetics of oxygen consumption rates against headspace-gas oxygen concentration observed in this experiment did not conform to Monod type kinetics depicted in **Fig. 10d**. The trend was more pronounced for the 5% MO – HD substrate. The profile showed that when the oxygen concentration in the headspace-gas was less than 15%, the oxygen consumption rate was close to zero, but was observed to increase dramatically with the increase of oxygen concentration.

Biological wastewater treatment uses bacterial mixed cultures to degrade organic load. The kinetics have often been described by the Monod equation as shown below:

$$\mu = \mu_{max} \frac{S}{K_s + S}$$

The equation shows that the maximum specific growth rate (μ_{max}) of the mixed culture is dependent on the concentration of the limiting substrate. In most wastewater treatment systems, oxygen supply is the limiting substrate (S).

When the limiting substrate is provided in excess such that the concentration is significantly larger than the substrate saturation constant (K_s), the second term becomes unity. The microbial activity should reach zero order growth kinetics under this condition where the specific growth rate (μ) is equal to μ_{max} [134]. However, the results gathered from this study showed that increasing oxygen concentration in the headspace-gas continued to increase degradation rate which deviates from the model's description.

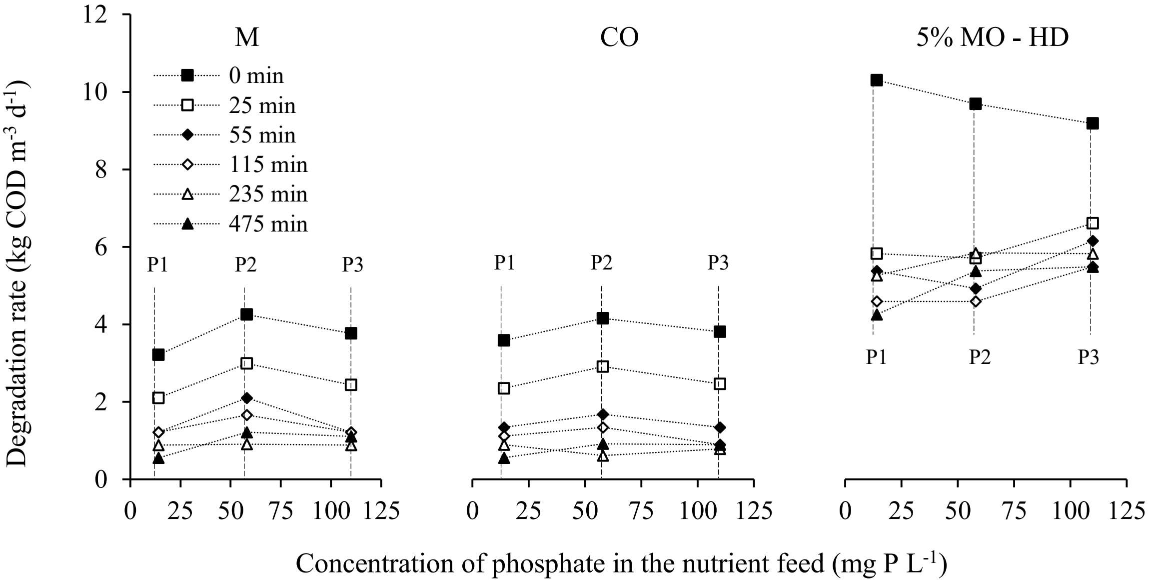
The observed trend for this study was different from the Monod type kinetics where reaction rate linearly increases with lower substrate concentrations, and then approaches a maximum at higher substrate concentrations. The kinetics exhibited by the 5% MO-HD oxygen consumption profile, as well for CO at 55 min headspace-gas exposure, was closer to a sigmoidal function.

An example of a sigmoidal growth model is the Gompertz function which has been used in the biological sciences to describe growth rates as a function of time [135]. Other sigmoidal models used for bacterial growth include Logistics, Richards, Schnutte, and Stannard, all of which are also time functions [136]. Few studies have described microbial kinetics as a function of substrate concentration using sigmoidal models. The study done by Namgung and Song [137] used a modified Monod-Gompertz equation to describe the growth of sulfur oxidizing bacteria (SOB) as a function of DO. The bacterial strain consumed oxygen in a similar sigmoidal profile as shown in this experiment.

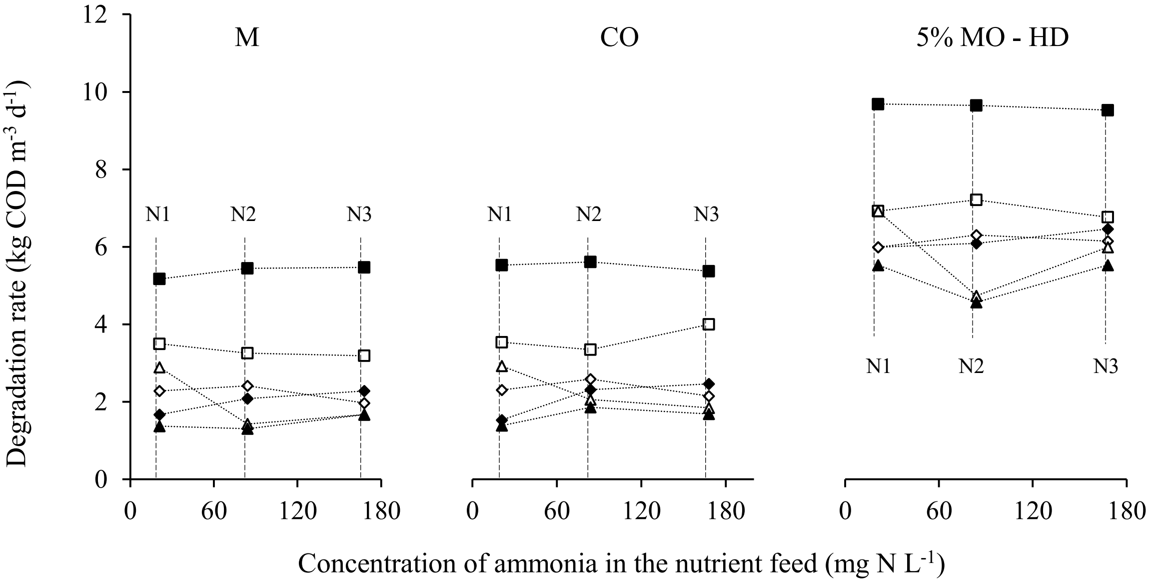
In terms of operational control for ICOP application, maintaining headspace-gas oxygen concentration at normal saturation is enough to give a reliable degradation performance. The maintenance of normal oxygen concentration is thought not to be very difficult because the gas-phase oxygen concentration in long sewer pipes do not vary greatly between 20 – 21 %O_2 [100].

5.3 Effect of Various Nutrient Concentrations in the Nutrient Feed

The degradation rates of the six preparations, P1, P2, P3, N1, N2, and N3, per lipid substrate were plotted against various nutrient concentrations in the nutrient feed (**Fig. 11**).



(A) Change of degradation rate with various concentrations of phosphate in the nutrient feed (Set P).



(B) Change of degradation rate with various concentrations of ammonia and other minerals in the nutrient feed (Set N).

Fig. 11 Change of degradation rate with various nutrient concentrations (M – margarine, CO – calcium oleate, 5% MO – HD – 5% methyl oleate in hexadecane; P1 – 14 mg phosphate/L phosphate, P2 – 58 mg phosphate/L, P3 – 110 mg phosphate/L; N1 – 21 mg nitrogen/L, N2 – 84 21 mg nitrogen/L, N3 – 168 21 mg nitrogen/L).

The effect of various nutrient concentrations in the nutrient feed was explored by varying the nutrient feed make-up. The results showed that there were no dramatic differences in the observed degradation rates found per set across substrates as seen for set P (**Fig. 11a**) with increasing phosphorous concentration and set N (**Fig. 11b**) with increasing nitrogen and mineral concentration in the nutrient feed. The rate profiles for all preparation sets showed a consistent trend for all substrates where extended periods without water flow decreased degradation rate. The trend agreed with the results found for the effect of media headspace-gas exposure time.

The investigation of the effect of various nutrient concentrations was conducted due to the thought that at longer extents without water flow, the nutrient supply to the biofilm could limit the degradation of lipids. This can happen due to the lesser frequency of nutrient feed being recirculated during 55, 115, 235, and 475 headspace-gas exposure conditions. If the nutrients are indeed lacking, the lesser frequency of recirculation means lesser supply of essential nutrients even with the excess of substrate leading to a decrease in degradation rate.

The results imply that nutrients and lipid substrates were in excess at all times and were not the rate-limiting factors in degradation. The degradation profile showed no dramatic change after 1 hr without flow even when the concentrations of nitrogen and phosphorous were already four times the original concentration as indicated by the plots of N3 and P3 for all substrates. Similarly, even at half the original concentration, the degradation profile showed no dramatic change as shown by the profile for P1 and P3. Given the supporting data, the primary cause of the decrease in degradation rate for all conditions was thought to be the supply of oxygen to the biofilm.

Lipids can potentially cause anaerobic conditions in sewer environments after accumulation which makes studies on enhancing its biodegradation relevant. In cases where it cannot be enhanced, the suppression of anaerobic conditions should be considered. Studies on the appropriate supplements for the suppression of anaerobic conditions in sewer environments have cited nitrate dosing into the sewer line in order to suppress sulfate-reducing and methanogenic conditions [138]. However, as both the literature and experimental results for this study suggest, the availability of oxygen and the maintenance of aerobic conditions still remain to be indispensable in degrading lipids [7].

CHAPTER 6

Summary and Concluding Remarks

6.1 Summary and Conclusions

Chapter 2 and 3 reviewed the related and relevant literature regarding the appropriate wastewater treatment systems to recommend for rural and peri-urban areas of developing countries, particularly the Southeast Asian region. It was found that flexibility and appropriateness of both technology and management systems are relevant. The review pointed that flexibility and appropriateness can be achieved through a synthesis of both CWCT and DWT systems. This can be realized through proper regard of the collection system.

The identification of the collection system as an essential tool for addressing wastewater treatment and sanitation concerns provided the significance to study sewer self-purification processes like the Intermittent Contact Oxidation Process (ICOP). This process enhances the biological removal of organic pollutants through enhancing biomass retention. The enhanced biomass retention is achieved through pipe surface modification by installing sponges with the pipe. The production of too much biomass coupled with the presence of accumulation-forming substances like lipids present within the sewer pipe may lead to clogging and eventual fouling of the sewer self-purification process.

In Chapters 4 and 5, the degradation behavior of lipids were explored with the application of the ICOP. This was done to explore the degradation behavior of ICOP and connect it to possible process control options which could prevent accumulations and fouling to occur. To do so, experiments on the effect of flow intermittency, headspace-gas exposure, and nutrient concentration were explored.

From the study, the following conclusions were drawn:

Wastewater treatment systems for rural and peri-urban areas in developing countries

1. Proposing either CWCT or DWT systems as stand-alone approaches to answer the need for wastewater treatment and sanitation in rural and peri-urban areas of developing countries cannot address all the identified concerns. In such cases, the synthesis of both systems would provide a flexible approach for wastewater treatment and sanitation.

2. The development of a technology that is flexible towards CWCT and DWT systems is relevant in realizing wastewater treatment and sanitation goals for rural and peri-urban regions of developing countries.
3. Focusing on the development and use of the collection system as a treatment technology through enhancing in-sewer purification is flexible to both CWCT and DWT systems but needs to be explored further for its treatment capacity and general performance.

Capability of ICOP to degrade various lipid types

1. At normal oxygen concentration, the experimental lipid COD degradation rate that ranged between 1.1 – 8.3 kg COD/($m^3 \cdot$ day) was observed with potential reaeration with water flow and with reaeration through intermittent media headspace-gas exposure.
2. Lipid degradation rates were affected by the substrate composition where an increase in chain length and saturation in the hydrocarbon profile of the lipids substrate negatively affects degradation rate.

Process control options for the in-sewer application of ICOP

1. Intermittent media headspace-gas exposure affected degradation rate wherein extended conditions without water flow decreased but sustained degradation at 24 – 46% of the highest estimated degradation rate.
2. Setting initial headspace-gas oxygen concentration to 25 $\%O_2$ generally increased degradation rate by 9 – 50% compared to the degradation rates for normal initial oxygen concentrations (20 – 21 $\%O_2$).
3. Nutrient concentration in the nutrient feed did not affect lipid degradation rate suggesting that they were not rate-limiting factors in lipid degradation.

This study has successfully explored lipid degradation behavior in the application of ICOP for in-sewer purification. Process control options were identified and tested for lipid and organic matter degradation. The control options include, but are not limited to, the maintenance of an aerobic environment by manipulating sewer headspace-gas concentration and manipulation of wastewater flow.

6.2 Concluding remarks

The results and conclusions of this study have led to the following remarks regarding further studies and applications of ICOP for the in-sewer treatment of lipids and of organic matter in sewage:

1) Studies on simulated anoxic and anaerobic environments relevant to lipid accumulations should be explored in order to identify other control options for lipid degradation.
2) Studies on the biofilm population relating to lipid degradation should be done to understand and enhance the performance of ICOP for in-sewer purification.
3) In gauging the degradation rate of ICOP for in-sewer purification, the decisions between volumetric or areal rate expressions should be clarified by identifying the aerobically active regions of the sponge media.
4) Sponge morphology, including its orientation upon installation, and how it affects degradation rates should be explored to enhance degradation rates.
5) Sewer oxygen concentration should be monitored upon application of ICOP to the sewer system. Even though normal oxygen concentration is reported to be maintained in long sewer pipes, the application of ICOP is thought to increase the oxygen consumption within the pipe which would lower oxygen concentration in the headspace-gas.
6) The identification of ICOP applied for in-sewer purification as an in-between technology to CWCT and DWT should be further clarified by using real-world models of the technology.

REFERENCES

[1] United Nations Economic and Social Council. *Progress towards Sustainable Development Goals* [internet]. Vienna: United Nations Economic and Social Council; 2017 p. 8 – 9. Available from: http://www.un.org/ga/search/view_doc.asp?symbol=E/2017/66&Lang=E [Accessed on 2018 April 15].

[2] Bieker S, Cornel P, Wagner M: Semicentralised supply and treatment systems: integrated infrastructure solutions for fast growing urban areas. *Water Sci. Technol.*, **61**(11), 2905 – 2913, 2010.

[3] Massoud MA, Tarhini A, Nasr JA: Decentralized approaches to wastewater treatment and management: Applicability in developing countries. *J. Environ. Manag.*, **90**, 662 – 669, 2009.

[4] Wilderer PA, Schreff D: Decentralized and centralized wastewater management: a challenge for technology developers. *Wat. Sci. Technol.*, **41**(1), 1 – 8, 2000.

[5] Libralato G, Ghirardini AV, Avezzù F: To centralise or to decentralise: an overview of the most recent trends in wastewater treatment management. *J. Environ. Manag.*, **94**, 61 – 68, 2012.

[6] Shoji T, Matsubara Y, Tamaki S, Matsuzaka K, Satoh H, Mino T: In-sewer treatment system on enhancing self-purification: performance and oxygen balance in pilot tests. *J. Water Envi. Tech.*, **13**(6), 427 – 439, 2015.

[7] Warith MA, Kennedy K, Reitsma R: Use of sanitary sewers as wastewater pre-treatment systems. *Waste Manag.,* **18**, 235 – 247, 1998.

[8] Marjaka IW, Miyanaga K, Hori K, Tanji Y, Unno H: Augmentation of self-purification capacity of sewer pipe by immobilizing microbes on the pipe surface. *Biochem. Eng. J.*, **15**, 69 – 75, 2003.

[9] Sophonsiri C, Morgenroth E: Chemical composition associated with different particle size fractions in municipal, industrial, and agricultural wastewaters. *Chemosphere*, **55**, 691 – 703, 2004.

[10] George J, Minel F, Grisenti M: Physical and hydrodynamical parameters controlling gas-liquid mass transfer. *Int. J. Heat Mass Transfer.* **37**(11). 1569 – 1578, 1994.

[11] Keener KM, Ducoste JJ, Holt LM: Properties influencing fat, oil, and grease deposit formation. *Water Environ. Res.*, **80**, 2241 – 2246, 2008.

[12] He X, Iasmin M, Dean LO, Lappi SE, Ducoste JJ, de los Reyes FL III: Evidence for fat, oil, and grease (FOG) deposit formation mechanisms in sewer lines. *Environ. Sci. Technol.*, **45**, 4385 – 4391, 2011.

[13] He X. de los Reyes FL III, Leming ML, Dean LO, Lappi SE, Ducoste JJ: Mechanisms of Fat, Oil and Grease (FOG) deposit in sewer lines. *Water Res.,* **47**, 4451 – 4459, 2013.

[14] He X, Zhang Q, Cooney MJ, Yan T: Biodegradation of fat, oil, and grease (FOG) deposits under various redox conditions relevant to sewer environment. *Appl. Microbiol. Biotechnol.,* **99**, 6059 – 6068, 2015.

[15] World Health Organization. Monitoring the achievement of the health-related Millennium Development Goals. Geneva: World Health Organization; 2013.

[16] Sachs JD: From Millennium Development Goals to Sustainable Development Goals. *Lancet,* **379**, 2206 – 2211, 2012.

[17] Ujang Z, Henze M: Sustainable Sanitation for Developing Countries. In: Ujang Z, Henze M. (eds.) *Municipal Wastewater Management in Developing Countries: Principles and Engineering*. London: IWA Publishing; 2006.

[18] Fisher FM: The economics of water dispute resolution, project evaluation and management: An application to the Middle East. *Int. J. Water Resour. D.*, 11(4), 377 – 390, 1995.

[19] Domenèch L: Rethinking water management: From centralised to decentralised water supply and sanitation models. *Documents d'Anàlisi Geogràfica*, **57**(2), 293 – 310, 2011.

[20] Wilderer PA: Decentralized versus centralized wastewater management. In: Lens P, Zeeman G, Lettinga G. (eds.) *Decentralised Sanitation and Reuse: Concepts, systems and implementation.* London: IWA Publishing; 2001.

[21] Elmasry M, Hawari A, Zayed T: An economic loss model for failure of sewer pipelines. *Structure and Infrastructure Engineering,* 2018. DOI: 10.1080/15732479.2018.1433693

[22] Engin GO, Demir I: Cost analysis of alternative methods for wastewater handling in small communities. *J. Environ. Manag.*, **79**, 267 – 363, 2006.

[23] Grau P: Low cost wastewater treatment. *Wat. Sci. Technol.*, **33**(8), 38 – 46, 1996.

[24] Burian SJ, Nix SJ, Pitt RE, Durrans SR: Urban wastewater management in the United States: Past, Present, and Future. *J. Urban Technol.*, **7**(3), 33 – 62, 2000.

[25] Vråle L. Some aspects on Norwegian practice. In: Eikum AS, Seabloom RW (eds.) *Proc. Alternative Wastewater Treatment: Low-cost Small Systems, Research and Development*, September 7 – 10 1981, Oslo, Norway. Dordrecht: D. Reidel; 1982, p. 9 – 22.

[26] Kawamura H, Odaka Y, Sannomiya T. Study on sewage treatment facility for unsewered areas. *Proc. 1st Specialist Conf. Municipal Water Management and Sanitation in Developing Countries,* Bangkok, Thailand. 2014 December 2 – 4.

[27] Butler D, Davies JW: Approaches to urban drainage. *Urban Drainage*. 3rd Ed. London: Spon Press; 2011. p. 17 – 28.

[28] Tavakol-Davani H, Goharian E, Hansen CH, Tavakol-Davani H, Apul D, Burian SJ: How does climate change affect combined sewer overflow in a system benefiting from rainwater harvesting systems? *Sustain. Cities Soc.*, **27**, 430 – 438, 2016.

[29] Hong SW, Choi YS, Kim SJ, Kwon G: Pilot-testing an alternative onsite wastewater treatment system for small communities and its automatic control. *Wat. Sci. Technol.*, **51**(10), 101 – 108, 2005.

[30] El-Gohary FA: DESAR treatment concepts for combined domestic wastewater. In: Lens P, Zeeman G, Lettinga G. (eds.) *Decentralised Sanitation and Reuse: Concepts, systems and implementation*. London: IWA Publishing; 2001.

[31] Ujang Z, Buckley C: Water and wastewater in developing countries: present reality and strategy for the future. *Wat. Sci. Technol.*, **46**(9), 1 – 9, 2002.

[32] Crites R, Tchobanoglous G: Small and Decentralized Wastewater Management Systems: An Overview. *Small and Decentralized Wastewater Management*. Boston: WCB/McGraw-Hill; 1998. p. 1 – 20.

[33] Mara DD: Water, sanitation and hygiene for the health of developing nations. *Public Health,* **117**, 452 – 456, 2003.

[34] Hamid HA, Ujang Z: Management of Decentralised Sewerage Systems. In: Ujang Z, Henze M. (eds.) *Municipal Wastewater Management in Developing Countries: Principles and Engineering*. London: IWA Publishing; 2006.

[35] Ford T: Understanding population growth in the peri-urban region. *Int. J. Popul. Goegr.*, **5**, 297 – 311, 1999.

[36] Hughes R, Ho G, Matthew K: Conventional small and decentralised wastewater systems. In: Ujang Z, Henze M. (eds.) *Municipal Wastewater Management in Developing Countries: Principles and Engineering*. London: IWA Publishing; 2006.

[37] Katukiza AY, Ronteltap M, Niwagaba CB, Foppen JWA, Kansiime F, Lens PNL: Sustainable sanitation technology options for urban slums. *Biotechnol. Adv.*, **30**, 964 – 978, 2012.

[38] Pathak B: Maintenance management of public toilets: Experience of a non-government organization. *Building and Environment.* **26**(3), 313 – 315, 1991.

[39] Philip H, Maunoir S, Rambaud A, Philippi, LS: Septic tank sludges: accumulation rate and biochemical characteristics. *Wat. Sci. Technol.*, **28**(10), 57 – 64, 1993.
[40] Yang XM, Yahashi T, Kuniyasu K, Ohmori H: On-site systems for domestic wastewater treatment (johkasous) in Japan. In: Lens P, Zeeman G, Lettinga G. (eds.) *Decentralised Sanitation and Reuse: Concepts, systems and implementation*. London: IWA Publishing; 2001.
[41] Zeeman G, Kujawa-Roeleveld K, Lettinga G: Anaerobic treatment systems for high strength domestic waste (water) streams. In: Lens P, Zeeman G, Lettinga G. (eds.) *Decentralised Sanitation and Reuse: Concepts, systems and implementation*. London: IWA Publishing; 2001.
[42] Keegan M, Kilroy K, Nolan D, Dubber D, Johnston PM, Misstear BDR, O'Flaherty V, Barrett M, Gill LW: Assessment of the impact of traditional septic tank soakaway systems on water quality in Ireland. *Wat. Sci Technol.*, **70**(4), 634 – 341, 2014.
[43] Yang YY, Toor GS, Wilson PC, Williams CF: Micropolutants in groundwater from septic systems: transformations, transport mechanisms, and human health risk assessment. *Water Res.*, **123***,* 258 – 267, 2017.
[44] Metcalf and Eddy, Inc., Tchobanoglous G, Stensel HD, Tsuchihashi R, Burton F, Abu-Orf M, Bowden G, Pfrang W: Attached Growth and Combined Biological Treatment Processes. *Wastewater Engineering: Treatment and Resource Recovery*. 5th Ed. New York: McGraw-Hill; 2014. p. 941 – 1058.
[45] Ho G: Small water and wastewater systems: pathways to sustainable development. *Wat. Sci. Technol.*, **48**(11 – 12), 7 – 14, 2004.
[46] Ho G: Technology for sustainability: the role of onsite, small and community scale technology. *Wat. Sci. Technol.*, **51**(10), 15 – 20, 2005.
[47] Ukita M, Shirota H, Nakanishi H: The option of appropriate system for wastewater treatment in low-density areas. *Wat. Sci. Technol.*, **28**(10), 49 – 56, 1993.
[48] Angelakis AN: Management of wastewater by natural treatment systems with emphasis on land-based systems. In: Lens P, Zeeman G, Lettinga G. (eds.) *Decentralised Sanitation and Reuse: Concepts, systems and implementation.* London: IWA Publishing; 2001.
[49] Henze M, Ujang Z, Soedjono E: Wastewater treatment technology for developing countries. In: Ujang Z, Henze M. (eds.) *Municipal Wastewater Management in Developing Countries: Principles and Engineering*. London: IWA Publishing; 2006.
[50] Picot B, Paing J, Sambuco JP, Costa RHR, Rambaud A: Biogas production, sludge accumulation and mass balance of carbon in anaerobic ponds. *Wat. Sci. Technol.*, **48**(2), 243 – 250, 2003.
[51] Paing J, Picot B, Sambuco JP, Rambaud A: Sludge accumulation and methanogenic activity in an anaerobic lagoon. *Wat. Sci. Technol.*, **42**(10 – 11), 247 – 255, 2000.
[52] Bangkok Metropolitan Administration. *Preparatory survey for Bangkok wastewater treatment project in Thailand.* Bangkok: Japan International Cooperation Agency; 2011.
[53] Maynilad. *Next generation: following 10 years of transformation: 2016 Maynilad annual report* [internet]. Manila: Maynilad; 2016. p. 38 – 39. Available from: http://www.mayniladwater.com.ph/uploaded/MAYNILAD-AR-2016_FINAL.PDF [Accessed on 2018 June 1].
[54] Manila Water. *Annual report: Sustainability report* [internet]. Manila: Manila Water; 2015. Available from: https://reports.manilawater.com/sustainability-report [Accessed on 2018 June 1].
[55] MLIT, MAFF, MoE: Manual on the preparation of prefectural plan for the development of sustainable wastewater management systems [internet]. Japan: MLIT; 2014. Available from: http://www.mlit.go.jp./mizukokudo/sewerage/mizukokudo_sewerage_tk_00277.html, in Japanese [Accessed on 2018 June 20].

[56] Association of Southeast Asian Nations. *ASEAN Member States* [internet]. Available from: http://asean.org/asean/asean-member-states [Accessed on 2018 June 1].

[57] Nguyen HM, Visvanathan C, Jegatheesan V. Performance of septic tanks as onsite sanitation system. *Proc. 4th Int. Symp. Southeast Asian Water Environment*, Bangkok, Thailand. 2006 December 6 – 8.

[58] Heng R, Heang V. *Cambodia municipal wastewater treatment system*. [Presentation] Current Status of the Planning of Municipal Wastewater Treatment System. Water Environment Partnership in Asia. 2016 July 28.

[59] Yim M, Bathna S, Irvine K. Storm and dry weather water quality characteristics in the Phnom Phen combined sewer system. *Proc. 6th Int. Symp. Southeast Asian Water Environment*, Bandung, Indonesia. 2008 October 29 – 31.

[60] Sirait NLE. *Sewerage development in Indonesia*. [Presentation] Conference on Watershed Management for Controlling Municipal Wastewater in South East Asia. Water Environment Partnership in Asia. 2016 July 28.

[61] Douangchanh V, Phosy N. *Waste water management and sanitation practice in Lao PDR*. [Presentation] Regional Policy Workshop of Stakeholders on Decentralized Wastewater Management Systems (DEWATS). United Nations Economic Commission for Asia and the Pacific. 2014 March 19 – 21.

[62] Phonvisai P. *Current situation and future visions of domestic wastewater treatment in Lao PDR*. [Presentation] WEPA 4th International Workshop. Water Environment Partnership in Asia. 2013 February 18 – 20.

[63] Ujang Z: Strategy and planning of sewerage infrastructures for developing countries: experience of Malaysia. In: Ujang Z, Henze M. (eds.) *Municipal Wastewater Management in Developing Countries: Principles and Engineering*. London: IWA Publishing; 2006.

[64] Sim LK, Balamurugan G: Urbanization and urban water problems in Southeast Asia: a case of unsustainable development. *J. Environ. Manag.*, **32**, 195 – 209, 1991.

[65] Aung Khaing Min. *Current status of the planning of municipal wastewater treatment system in Myanmar*. [Presentation] Conference on Watershed Management for Controlling Municipal Wastewater in South East Asia. Water Environment Partnership in Asia. 2016 July 28.

[66] Gonzales EA, Cleofas LC. *Water quality guidelines and effluent standards and its implementation in the Philippines*. [Presentation] Conference on Watershed Management for Controlling Municipal Wastewater in South East Asia. Water Environment Partnership in Asia. 2016 July 28.

[67] Cabral MCE. *Approaches for planning wastewater and septage systems in the Philippines*. [Presentation] Conference on Watershed Management for Controlling Municipal Wastewater in South East Asia. Water Environment Partnership in Asia. 2016 July 28.

[68] Sujaritpong S, Nitivattananon V: Factors influencing wastewater management performance: Case study of housing estates in suburban Bangkok, Thailand. *J. Environ. Manag.*, **90**, 455 – 465, 2009.

[69] Surichayan C, Nitivattananon V, Amin ATMN: Potential of decentralized wastewater management for urban development: Case of Bangkok. *Habitat Int.*, **36**, 85 – 92, 2012.

[70] Yusuf MA, Takizawa S, Katayama H. Wastewater management of Bangkok and Dhaka Mega City. *Proc. 4th Int. Symp. Southeast Asian Water Environment*, Bangkok, Thailand. 2006 December 6 – 8.

[71] Nguyen HT. *Drainage and wastewater treatment planning in Vietnam*. [Presentation] Conference on Watershed Management for Controlling Municipal Wastewater in South East Asia. Water Environment Partnership in Asia. Water Environment Partnership in Asia. 2016 July 28.

[72] Quan PV, Furumai H, Kurisu F, Kasuga I. Surface water pollution due to discharging from sewerage system in downtown of Hanoi. *Proc. 6th Int. Symp. Southeast Asian Water Environment*, Bandung, Indonesia. 2008 October 29 – 31.

[73] Ouano EAR: Domestic wastewater treatment and disposal in the Philippines. *Wat. Sci. Technol.*, **18**(10), 23 – 32, 1986.

[74] Pham NB, Muhammad Sonny A. Septage Management: Situation Analysis and Business Assessment in Urban Area of Indonesia [internet]. Japan: Institute for Global Environmental Strategies; 2017. Available from: https://pub.iges.or.jp/pub/septage-management-situation-analysis-and [Accessed on 2018 April 20]

[75] Nguyen VA. Water environment and water pollution control in Vietnam: Overview of status and measures for future. *Proc. 1st Int. Symp. Southeast Asian Water Environment*, Bangkok, Thailand. 2003 October 23 – 25.

[76] Panuvatvanich A, Surinkul N, Koottatep T. Decentralized wastewater treatment systems for small-scale communities. *Proc. 2nd Int. Symp. Southeast Asian Water Environment*, Hanoi, Vietnam. 2004 December 1 – 3.

[77] Memon MA, Imura H. Impact of globalization and economic development on urban water and wastewater management in Asia. *Proc. 1st Int. Symp. Southeast Asian Water Environment*, Bangkok, Thailand. 2003 October 23 – 25.

[78] Koottatep T, Chapagain SK, Polprasert C, Panuvatnavich A: Sanitation situations in selected Southeast Asian countries and application of innovative technologies. *Environ. Dev. Sustain.*, **20**, 495 – 506, 2018.

[79] Kim YK, Seo IS, Jung NC, Byun JH: Status analysis and strategic framework for sanitation management in Asia and Africa. *Wat. Sci. Technol.*, **56**(5), 25 – 31, 2007.

[80] Kamal ASM, Goyer K, Koottatep T, Amin ATMN: Domestic wastewater management in South and Southeast Asia: the potential benefits of a decentralised approach. *Urban Water J.*, **5**(4), 345 – 354, 2008.

[81] Jiawkok S, Petchrat S, Koottatep T. Evaluation of onsite sanitation systems and faecal sludge management in Thailand. *Proc. 5th Int. Symp. Southeast Asian Water Environment*, Hanoi, Vietnam. 2004 December 1 – 3.

[82] Marcotullio PJ: Urban water-related environmental transitions in Southeast Asia. *Sustain. Sci.*, **2**, 27 – 54, 2007.

[83] Asian Development Bank. *Water in Asian Cities*. Manila: Asian Development Bank; 2004.

[84] Pomeroy RD, Parkhurst JD. Self-purification in sewers. *Proc. 6th Int. Conf. on Water Pollut. Res.*, Jerusalem, Israel. 1972 June 18 – 23.

[85] Green M, Shelef G, Messing A: Using the sewar system main conduits for biological treatment – Greater Tel-Aviv as a conceptual model. *Water Res.*, **19**(8), 1023, 1985.

[86] Shahvi S, Orsi E, Canziani R, Larcan E, Becciu G: Aerobic transformations of organic matters in sewer wastewater, a case study of Milan, Italy. *Urban Water J.*, **14**(10), 1058 – 1064, 2017.

[87] Jensen H, Biggs CA, Karunakaran E: The importance of sewer biofilms. *WIREs Water,* **3**, 487 – 494, 2016.

[88] Hvitved-Jacobsen T, Vollertsen J, Nielsen AH: *Sewer Processes: Microbial and Chemical Process Engineering of Sewer Networks*. 2nd Ed. Boca Raton: CRC Press; 2013.

[89] Raunkjær K, Hvitved-Jacobsen T, Nielsen PH: Transformation of organic matter in a gravity sewer. *Water Environ. Res.*, **67**(2), 181 – 188, 1995.

[90] Kaijun W, Zeeman G, Lettinga G: Alteration of sewage characteristics upon aging. *Wat. Sci. Technol.*, **31**(7), 191 – 200, 1995.

[91] Bjerre HL, Hvitved-Jcobsen T, Teichgräber B, te Heesen D: Experimental procedures characterizing transformations of wastewater organic matter in the Emscher River, Germany. *Wat. Sci. Technol.*, **31**(7), 201 – 212, 1995.

[92] Reguiero-Picallo M, Anta J, Suarez J, Puertas J, Jacome A, Naves J: Characterization of sediments during transport of solids in circular sewer pipes. *Wat. Sci. Technol.*, **2017**(1), 8 – 18, 2017.

[93] Yun Z, Yun GH, Lee HS, Yoo TU: The variation of volatile fatty acid compositions in sewer length, and its effect on the process design of biological nutrient removal. **67**(12), 2753 – 2760, 2013.

[94] Raunkjær K, Hvitved-Jacobsen T, Nielsen PH: Measurement of pools of protein, carbohydrate and lipid in domestic wastewater. *Water Res.*, **28**(2), 251 – 262, 1994.

[95] Nielsen PH, Raunkjær K, Norsker NH, Jensen NA, Hvitved-Jacobsen T: Transformation of wastewater in sewer systems – a review. *Wat. Sci. Technol.*, **25**(6), 17 – 31, 1992.

[96] Chen GH, Ozaki H, Terashima Y: Modeling of the simultaneous removal of organic substances and nitrogen in biofilm. *Wat. Sci. Technol.*, 21, 791 – 804, 1989.

[97] Özer A, Kasirga E: Substrate removal in long sewer lines. *Wat. Sci. Technol.*, **31**(7), 213 – 218, 1995.

[98] Koch CM, Zandi I: Use of pipelines as aerobic biological reactors. *J. Water Pollut. Control Fed.*, **45**(12), 2537–2548, 1973.

[99] Garcia-Ochoa F, Gomez E, Santos VE, Merchuk JC: Oxygen uptake rate in microbial processes: An overview. *Biochem. Eng. J.*, **49**, 289 – 307, 2010.

[100] Huisman JL, Weber N, Gujer W: Reaeration in sewers. *Water Res.*, **38**, 1089 – 1100, 2004a.

[101] Almeida MC, Butler D, Davies JW: Modelling in-sewer changes in wastewater quality under aerobic conditions. *Wat. Sci. Technol.*, **39**(9), 63 – 71, 1999.

[102] Manandhar UK, Schroder H: Sewage circulating reactor – an approach to recirculating wastewater in sewers. *Environ. Technol*., **16**, 201 – 212, 1995.

[103] Baban A, Talinli: Modeling of organic matter removal and nitrification in sewer systems – an approach to wastewater treatment. *Desalination*. **246**, 640 – 647, 2009.

[104] Marjaka IW, Miyanaga K, Hori K, Tanji Y, Unno H: Augmentation of self – purification capacity of sewer pipe by immobilizing microbes on the pipe surface. *Biochem. Eng. J.*, **15**, 69 – 75, 2003.

[105] Tanji Y, Sakai R, Miyanaga K, Unno H: Estimation of the self-purification capacity of biofilm formed in domestic sewer pipes. *Biochem. Eng. J.*, **31**, 96 – 101, 2006.

[106] Satoh H: Challenged of restoring and rehabilitating sewer systems damaged by the great East Japan earthquake and tsunami. *J. JSCE.*, **5**, 279 – 297, 2017.

[107] Mino T, Van Loosdrecht MCM, Heijnen JJ: Microbiology and biochemistry of the enhanced biological phosphate removal process. *Wat. Res.*, **32**(11), 3193 – 3207, 1998.

[108] Huisman JL, Gasser T, Gienal C, Kühni M, Krebs P, Gujer W: Quantification of oxygen fluxes in long gravity sewer. *Water Res.*, **28**, 1237 – 1247, 2004b.

[109] Chipasa KB, Mędrzycka K: Behavior of lipids in biological wastewater treatment process. *J. Ind. Micribiol. Biotechnol.*, **33**, 635 – 645, 2006.

[110] Wallace T, Gibbons D, O'Dwyer M, Curran TP: International evolution of fat, oil and grease (FOG) waste management – A review. *J. Environ. Manag.*, **187**, 424 – 435, 2017.

[111] Becker P, Köster D, Popov MN, Markossian S, Antranikian G, Markl H: The biodegradation of olive oil and the treatment of lipid-rich wool scouring wastewater under aerobic thermophilic conditions. *Water Res.*, **33**(3), 653 – 660, 1999.

[112] He X, de los Reyes III FL, Ducoste JJ: A critical review of fat, oil, grease (FOG) in sewer collection systems: Challenges and control. *Crit. Rev. Environ. Sci. Technol.*, **47**(13), 1191 – 1217, 2017.

[113] Chao AC, Yang W: Treatment of wool scouring wastewater. *J. Water Pollut. Control Fed.*, **53**, 311 – 317, 1981.

[114] Uemura S, Okubo T, Takahashi M, Kubota K, Harada H: Evaluation of water distribution and oxygen ass transfer in sponge support media for a down-flow hanging sponge reactor. *Int. J. Environ. Res.*, **10**(2), 265 – 272, 2016.

[115] Madigan M, Martinko J, Bender K, Buckley D, Stahl D: Metabolic Diversity of Microorganisms. *Brock Biology of Microorganisms*.14th Ed. England: Pearson; 2015. p. 403 – 456.

[116] McMurry J, Begley TP: Lipids and Their Metabolism. *The Organic Chemistry of Biological Pathways*. 2nd Ed. England: Roberts and Company Publishers; 2016. p. 122 – 130.

[117] Matsumiya Y, Wakita D, Kimura A: Isolation and characterization of a lipid-degrading bacterium and its application to lipid-containing wastewater treatment. *J. Biosci. Bioeng.*, **103**(4), 325 – 330, 2007.

[118] Okuda SI, Ito K, Ozawa H, Izaki K: Treatment of lipid-containing wastewater using bacteria which assimilates lipids. *J. Ferment. Bioeng.*, **71**(6), 424 – 429, 1991.

[119] Wakelin NG, Forster CF: An investigation into microbial removal of fats, oils and greases. *Bioresour. Technol.*, **59**, 37 – 43, 1997.

[120] Mongkolthanaruk W, Dharmsthiti S: Biodegradation of lipid-rich wastewater by a mixed bacterial consortium. *Int. Biodeterior. Biodegradation*, **50**, 101 – 105, 2002.

[121] Najafpour G, Yieng HA, Younesi H, Zinatizadeh A: Effect of organic loading on performance of rotating biological contactors using Palm Oil Mill effluents. *Process Biochem.*, **40**, 2879 – 2884, 2005.

[122] Safa M, Alemzadeh I, Vossoughi M: Biodegradability of oily wastewater using rotating biological contactor combined with an external membrane. *J. Environ. Health Sci. Eng.*, **12**, 117 – 121, 2014.

[123] El-Masry MH, El-Bestawy E, El-Adl NI: Bioremediation of vegetable oil and grease from polluted wastewater using a sand biofilm system. *World J. Microbiol. Biotechnol.*, **20**, 551 – 557, 2004.

[124] Wan TJ, Shen SM, Hwang HY: Soybean oil biodegradation using *Pseudomonas aeruginosa* attached on porous ceramic or polyurethane. *Arab. J. Sci. Eng.*, **38**, 1025 – 1030, 2013.

[125] Tyagi RD, Tran FT, Chowdhury KMM: Biodegradation of petroleum refinery wastewater in modified rotating biological contactor with polyurethane foam attached to the disks. *Wat. Res.*, **27**(1), 91 – 99, 1993.

[126] Al-Awadhi H, Al-Hasan RH, Sorkhoh NA, Salamah S, Radwan SS: Establishing oil-degrading biofilms on gravel particles and glass plates. *Int. Biodeterior. Biodegradation*. **51**, 181 – 185, 2003.

[127] Hashimoto S, Tanaka N, Suzuki M, Inoue A, Takizawa H, Kosaka I, Tanaka K, Tantasirin C, Tangtham N: Soil respiration and soil CO_2 concentration in a tropical forest, Thailand. *J. For. Res.*, **9**, 75 – 79, 2004.

[128] Keith H, Wong SC: Measurement of soil CO_2 efflux using soda lime absorption: Both quantitative and reliable. *Soil Biol. Biochem.*, **38**, 1121 – 1131, 2006.

[129] Bird RB, Stewart WE, Lightfoot EN: Concentration Distributions in Solids and in Laminar Flow. *Transport Phenomena*. 2nd Ed. New York: Wiley; 2002. p. 543 – 581.

[130] Jahn A, Nielsen PH: Cell biomass and exopolymer composition in sewer biofilms. *Wat. Sci. Technol.*, **37**(1), 17 – 24, 1998.

[131] Bishop PL: The effect of biofilm heterogeneity on metabolic processes. In: Wuertz S, Bishop PL, Wilderer PA. (eds.) Biofilms in Wastewater Treatment: An Interdisciplinary Approach. London: IWA Publishing; 2008.

[132] De Jonge H, Freijer JI, Verstraten JM, Westerveld J: Relation between bioavailability and fuel oil hydrocarbon composition in contaminated soils. *Environ. Sci. Technol.*, **31**, 771 – 775, 1997.

[133] Varjani SJ: Microbial degradation of petroleum hydrocarbons. *Bioresour. Technol.*, **223**, 277 – 286, 2017.

[134] Seviour R, Nielsen PH: *Microbial Ecology of Activated Sludge*. London: IWA Publishing; 2010.

[135] Marshall AW, Olkin I: Gompertz and Gompertz-Makeham Distributions. *Life Distributions: Structure of Nonparametric, Semiparametric, and Parametric Families*. New York: Springer; 2007. p. 363 – 398.

[136] Zwietering MH, Jogerburger J, Rombouts FM, van't Riet K: Modelling of the bacterial growth curve. *Appl. Environ. Microbiol.*, **56**(6), 1875 – 1881, 1990.

[137] Namgung HK, Song JH: The effect of oxygen supply on the dual growth kinetics of *Acidithiobacillus thioxidans* under acidic conditions for biogas desulfurization. *Int. J. Environ. Res. Public Health*, **12**, 1368 – 1386, 2015.

[138] Mohanakrishnan J, Gutierrez O, Sharma KR, Guisasola A, Werner U, Meyer RL, Keller J, Yuan Z: Impact of nitrate addition on biofilm properties and activities in rising main sewers. *Water Res.*, **43**, 4225 – 4237, 2009.