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Exploring Intermittent Contact Oxidation Process for Enhanced In-sewer Purification at Sewer Upstream

(下水道上流部における管路内下水浄化促進のための間欠接触酸化法の適用性に関する検討)

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EXPLORING INTERMITTENT CONTACT OXIDATION PROCESS

FOR ENHANCED IN-SEWER PURIFICATION AT SEWER UPSTREAM

ABSTRACT

The modern sewer was designed as a transportation tool of sewage, and wastewater treatment plant (WWTP) was constructed at the end of sewer to purify sewage. The sewer and WWTP system successfully protects public health and receiving water body. Such system, however, does not fulfill some criteria for environmental sustainability. A technology that reduces energy consumption for sewage treatment is the in-sewer purification technology, by actively utilizing biological reactions in sewer to purify sewage. Natural in-sewer purification can be enhanced by applying intermittent contact oxidation process (ICOP) in sewer. Application of ICOP is recommended at sewer upstream. Still, at sewer upstream the characteristics of sewage flow is poorly understood, and performance of ICOP under such condition remains unknown.

This study aims at exploring the potential of applying ICOP at sewer upstream for enhanced in-sewer purification to improve environmental sustainability in wastewater management. The aim encompasses three specific objectives. The first specific objective is to gain an understanding on in-sewer purification and sewer upstream by extensive literature review (Chapter 2). The second objective is to explore performance of ICOP under sewer upstream conditions with lab-scale experiment (Chapter 3). The third objective is to clarify contribution from in-sewer purification to environmental sustainability in wastewater management, through scenario analysis and discussion on wastewater management paradigm (Chapter 4).

The review in Chapter 2 summarized a timeline of in-sewer purification, and specifically focused on enhanced in-sewer purification and development of ICOP. For the application of in-sewer purification, sewer upstream was proposed. At sewer upstream, sewage quantity and quality is highly varied. Sewage flow pattern is characterized by intermittency, prevailing dry condition, and hydraulic instability.

In Chapter 3, a lab-scale ICOP reactor was constructed with sponge media installed in pipe. The sponge media retained microorganisms while being subject to intermittent water flow, so that oxygen supply was guaranteed. To reflect a sewer upstream condition, synthetic sewage and tap water was introduced into the reactor following a simplified flow pattern, including small volume of synthetic sewage flow, idle time with media exposure to air, large volume of tap water flow, and another idle time with media exposure to air. Under this pattern, organic matter removal efficiency was rather stable regardless of the extent of idle time. Explanation for the stable performance, even with extremely short sewage contact time, was attributed to the physical absorbance of sponge together with the carbon storage by microorganisms. The average organic matter removal rate was 2 gCOD/(L-sponge · d), based on which pollutant removal at sewer upstream was estimated. The estimated performance, as well as the stability observed in experiment, favored application of ICOP at sewer upstream.

As for Chapter 4, energy consumption for sewage treatment with ICOP was calculated, for a virtual community with high, medium, and low population density. The energy saving was up to 80% for area with medium to low population density. Thus, application of ICOP was proposed for cluster system with satellite WWTP. For the cluster system, water reuse could be adopted to form a closed water loop, which further reduced net water extraction from environment.

This study yielded an insight into application of ICOP at sewer upstream. The ICOP is suggested as a measure to enhance in-sewer purification, and as a choice for greater environmental sustainability in wastewater management.

Keywords: intermittent contact oxidation process, sewer upstream, wastewater management, in-sewer purification

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TABLE OF CONTENTS

LIST OF TABLES viii

LIST OF FIGURES ix

LIST OF ABBREVIATIONS x

LIST OF UNITS OF MEASUREMENTS xi

1 INTRODUCTION 1

1.1 Research Background 1
1.2 Research Objective 2
1.3 Manuscript Structure 3

2 IN-SEWER PURIFICATION AND SEWER UPSTREAM FOR ITS APPLICATION 5

2.1 Sewer Process and In-sewer Purification 5
2.1.1 Sewer process 5
2.1.2 In-sewer purification 6
2.1.3 Enhanced in-sewer purification 7
2.2 Sewer Upstream 8
2.3 Sewage Quantity, Quality and Flow Pattern at Sewer Downstream 9
2.4 Sewage Quantity & Quality at Sewer Upstream 11
2.4.1 Household appliances 11
2.4.2 Sewage quantity and quality from household appliances 11
2.4.3 Relative contribution from household appliances 13
2.5 Sewage Flow Pattern At Sewer Upstream 14
2.5.1 Frequency, duration and water flow rate of household appliance usage 15
2.5.2 Sewage flow pattern at sewer upstream 16
2.6 Chapter Summary 17

3 INTERMITTENT CONTACT OXIDATION PROCESS UNDER SEWER UPSTREAM CONDITION 19

3.1 Materials and Methods 19
3.1.1 Experimental setup 19
3.1.2 Simplified flow pattern 21
3.1.3 Monitoring of cycles 21
3.1.4 Effect of temperature 23
3.1.5 Polyhydroxyalkanoate (PHA) analysis 23
3.2 Results 24
3.2.1 TOC removal efficiency 24
3.2.2 Headspace oxygen consumption 26
3.2.3 Oxygen balance 28
3.2.4 Variation of PHA 29
3.3 Discussions 30
3.3.1 Mechanisms of organic matter removal 30
3.3.2 Carbon flow model and influencing factors 31
3.3.3 Organic matter load and removal rate 33
3.3.4 Estimation of performance at sewer upstream 33
3.3.5 PHA generation and reflections on experimental methods 34
3.4 Chapter Summary 35

4 IN-SEWER PURIFICATION AND ENVIRONMENTAL SUSTAINABILITY IN WASTEWATER MANAGEMENT 36
4.1 Overview 36
4.2 Energy Consumption Reduced by In-sewer Purification 38
4.2.1 Scenario settings and parameters 38
4.2.3 Results and discussion 40
4.3 New Wastewater Management Paradigm with In-sewer Purification 41
4.3.1 System proposal: closed water loop at cluster scale 41
4.3.2 Expected benefits 43
4.3.3 Spatial and temporal scale 43
4.4 Further Extension from New Paradigm 44
4.5 Suggestion for Application and Limitations at Current Stage 45
4.5.1 Suggestion for application 45
4.5.2 Limitations at current stage 46
4.6 Chapter Summary 47
5 CONCLUSIONS 49
5.1 Key Findings 49
5.2 Limitations and suggestions 50
REFERENCES 51
APPENDIX 57

LIST OF TABLES

Table 1 Quantity of sewage from each appliance 12

Table 2 Quality of sewage from each appliance 13

Table 3 Share of each household appliance in sewage quantity 14

Table 4 Frequency, duration and rate of water flow rate of household appliance usage 15

Table 5 COD removal and energy consumption for different scenarios 41

LIST OF FIGURES

Fig 1 Research framework....4

Fig 2 Microorganisms in a typical gravity sewer and relevant activities....6

Fig 3 A timeline of study on sewer processes and related branches....7

Fig 4 ICOP applied in sewer pipe as enhanced in-sewer purification....8

Fig 5 An illustration of sewer upstream....9

Fig 6 A typical sewage flow pattern at sewer downstream, qualitative....10

Fig 7 Household appliances and classification of sewage at sewer upstream....11

Fig 8 A typical sewage flow pattern at sewer upstream....17

Fig 9 Experimental setup of ICOP reactor....19

Fig 10 Proposal for simplified upstream sewage flow pattern....20

Fig 11 TOC removal efficiency, mass of loaded and outlet TOC.....24

Fig 12 TOC removal efficiency, mass of loaded and outlet TOC under low temperature....25

Fig 13 A case of headspace oxygen concentration variation within a cycle.....26

Fig 14 Variation of HOCR within a cycle.....27

Fig 15 Variation of HOCR within a cycle under low temperature....28

Fig 16 Oxygen balance of R_1....28

Fig 17 Oxygen balance of R_1 and R_2 under low temperature....29

Fig 18 Variation of PHA within a cycle....29

Fig 19 Model proposal for carbon flow in an ICOP reactor under feast-famine condition....32

Fig 20 Organic matter load and removal rate....33

Fig 21 A schematic of a) centralized wastewater management system, b) decentralized and cluster wastewater management system....37

Fig 22 Sewer network layout for different scenarios, a) high population density, b) medium population density, c) low population density....39

Fig 23 A closed water loop system and a traditional centralized system....42

Fig 24 Proposed framework to evaluate optimum spatial scale for a closed water loop system....44

Fig 25 Extension of a closed water loop system....45

LIST OF ABBREVIATIONS

BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
DPR	Direct Potable Reuse
FOGs	Fat, Oil and Greases
F/M ratio	Food to Microorganism ratio
HOC	Headspace Oxygen Consumption
HOCR	Headspace Oxygen Consumption Rate
HRT	Hydraulic Retention Time
ICOP	Intermittent Contact Oxidation Process
IPR	Indirect Potable Reuse
LCA	Life Cycle Analysis
NPR	Non-direct Potable Reuse
OUR	Oxygen Utilization Rate
PHA	Polyhydroxyalkanoate
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorous
TSS	Total Suspended Solids
VFAs	Volatile Fatty Acids
WWTP	Wastewater Treatment Plant

LIST OF UNITS OF MEASUREMENTS

°C	degree Celcius
cap	capita
cm	centimeter
d	day
g	gram
h	hour
ha	hectare
km	kilometer
L	liter
m	meters
mg	milligram
min	minute
mL	milliliter
mm	millimeter
mol	mole
s	second

CHAPTER 1 INTRODUCTION

1.1 Research Background

Modern sewer was developed with a primary objective to protect public health and sanitation in 19th century (1, 2). At that time, industrial revolution and rapid urbanization in the western world gave rise to high population density in urban area. Meanwhile, management of sewage was still primary, relying majorly on cesspool and open conduit. High population density and lack of proper sanitation led to widespread of the fatal disease cholera that claimed millions of lives. With the notion to separate human from waste gaining importance, modern sewer was constructed to transport sewage away from the city (3).

A secondary objective, to protect water environment, was attached to modern sewer system later in 20th century (3, 4). Before that, large amount of sewage had been discharged through sewer into natural water body in most cases without treatment. This approach generated unhindered pollution of environment and degradation of ecosystem. To address these issues, wastewater treatment plant (WWTP) was included at the very end of a sewer network, removing pollutants from sewage to a safe extent before discharge. Sewer and WWTP constitute the most widely applied centralized wastewater management system in developed world.

A third but same vital objective is nominated for wastewater management in 21st century, that greater environmental sustainability should be achieved (4, 5). The issue of sustainability originates from growing needs of human in contrast with finite nature of resources and high-quality energy (3, 6). In the field of wastewater management, the centralized system is still sub-optimal with many sustainability-related issues unsolved. Concerns related with centralized wastewater management are rising on energy and chemical consumption, loss of chance to reuse nutrients, and emerging micropollutants and heavy metal in treated sewage (7). And in developing world, providing the centralized system for all citizens is greatly limited by finance and resource availability (7, 8). Lack of proper sanitation is further a driver of water pollution, and hence available water resource becomes scarcer. To ensure better life quality of everyone, now and into the future, relying solely on current wastewater management system is inadequate (9).

To achieve greater environmental sustainability, the overall paradigm of wastewater management needs to be reconsidered (3, 10). The concept of decentralization is gaining popularity, that is, to reduce the reliance on large-scale infrastructure and to manage sewage close to its source (11). A cluster scale system, as a transition from single household level system to centralized system, demonstrates potential to achieve energy neutrality, water reuse, and nutrient recovery. Another concept is to form a closed water loop, by reducing net water extraction from natural environment and reuse treated sewage to the maximum (12).

Sustainability of current system is also promoted by actively integrating new technologies with higher efficiency, one of which is in-sewer purification. In-sewer purification is to control and utilize microbial and chemical processes in sewer to improve sewage quality during transportation in sewer (13, 14). If in-sewer purification is successfully introduced, it can function as a supplement or substitute for traditional wastewater treatment plant, reducing chemical, energy cost and capital investment for sewage treatment.

The capacity of natural in-sewer purification is usually insufficient compared to sewage volume (15), and measures are being sought to enhance in-sewer purification (15, 16). In a recent practice, a double-layer pipe was utilized to treat municipal sewage, with upper layer to transport sewage and lower layer to install sponge media (17). Sponge media provides habitat for microorganisms (18), which receive sewage flow from upper layer intermittently. Here, oxygen is supplied to microorganisms in two mechanisms: one of them is the enhanced reaeration of sewage when sewage drops from upper layer to bottom layer, and another is the intermittent exposure of microorganisms to air during low flow. The latter mechanism where microorganisms are exposed to sewage and air intermittently is referred to as intermittent contact oxidation process (ICOP) in this thesis. While double layer pipe structure showed high performance because oxygen is supplied to microorganisms by the two mechanisms, when the flow is low, sewage may run only on the upper layer and the performance may be significantly lowered. For low-flow gravity sewer with sufficient oxygen supply, ICOP alone may function effectively to enhance in-sewer purification.

Sewer upstream is proposed for application of ICOP to enhance in-sewer purification. Sewer upstream is defined as the aggregation of house sewer and lateral sewer (19). Sewer upstream is characterized by low sewage flow, long pipe length in accumulation, long hydrological retention time (HRT), and high share of biodegradable substrate, which guarantee potential for in-sewer purification. Nevertheless, characteristics of sewage flow at sewer upstream are not fully understood yet, which seems to be an obstacle for further advancement of ICOP.

1.2 Research Objective

Performance of ICOP under sewer upstream condition is still unknown. Here, the objective of this study is to explore the potential of applying ICOP at sewer upstream for enhanced in-sewer purification, as well as greater environmental sustainability in wastewater management system. Three specific objectives are embodied in the general objective.

The first specific objective is to conduct an extensive review of in-sewer purification and sewer upstream. The discussion primarily provides a timeline of the development of in-sewer purification, with special attention on enhanced in-sewer purification. Then, the topic moves on to sewer upstream, with its potential for utilizing in-sewer purification. For the following sections, characteristics of sewage at sewer upstream, containing sewage quantity, quality, and flow pattern, are reviewed in detail.

Following the literature review, the second objective is to explore performance of ICOP under sewer upstream conditions, as a measure of enhanced in-sewer purification. This is achieved by constructing a lab-scale ICOP reactor, operating it under a simplified sewage flow pattern, and evaluating total organic carbon (TOC) removal. Possible mechanism for organic matter removal, factors influencing system performance, and evaluation of system performance are the main components of the discussion.

The third objective propels the dialogue to a broader perspective, seeking implications on sustainable wastewater management through literature review and semi-quantitative analysis. The narrative here presents a brief review of current wastewater management systems, why they are not sustainable, and what is a sustainable system. Then, benefits inside a system with in-sewer purification are explained, especially in terms of environmental sustainability. To illustrate this idea, a case of incorporating ICOP at sewer upstream is discussed. Finally, this story ends with an overview of possible challenges for implementing in-sewer purification in real world.

1.3 Manuscript Structure

This manuscript is divided into five chapters, from a general overview all the way to a specific point of unknown, then back to a general discussion with findings from that point (**Fig 1**). Chapter 1 provides an introduction for this study, including background information, the unknown, research objective, and research framework. Chapter 2 corresponds to the first objective, summarizing studies about in-sewer purification and characteristics of sewage at sewer upstream. Chapter 3 serves for the second objective, presenting a lab scale experiment with ICOP reactor running under simulated sewer upstream condition. Then, in Chapter 4 the discussion seeks inspirations for greater environmental sustainability in wastewater management system by introducing in-sewer purification at sewer upstream. Finally, Chapter 5 summarizes findings, limitations and recommendations.

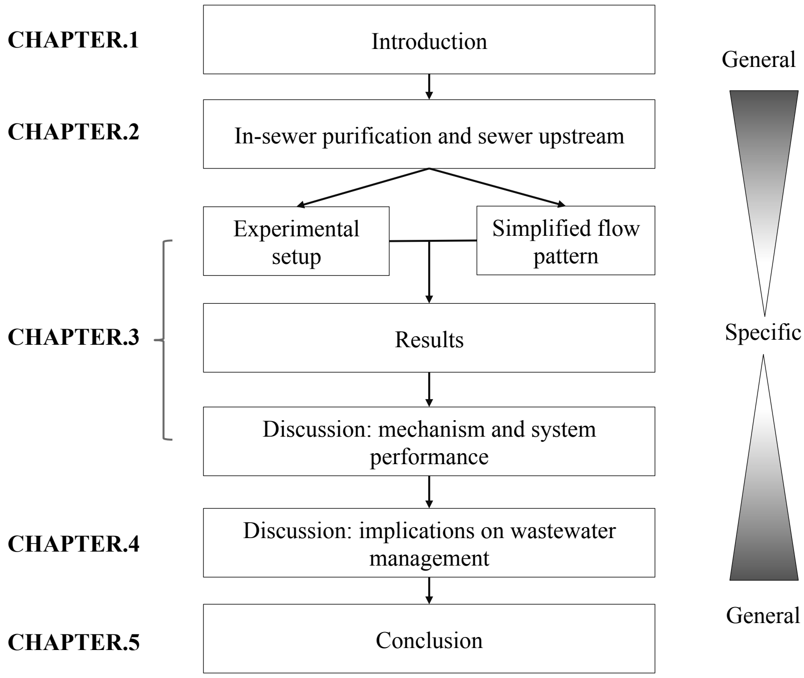


Fig 1 Research framework

CHAPTER 2 IN-SEWER PURIFICATION AND SEWER UPSTREAM FOR ITS APPLICATION

The objective of this chapter is to provide a review of in-sewer purification and sewer upstream. Structure of this chapter is arranged as follows. First, in Section 2.1 a timeline for the development of in-sewer purification is summarized, with particular interest on measures to enhance natural in-sewer purification. Then, definition of sewer upstream, relevant statistics and why sewer upstream is suitable for in-sewer purification are explained (Section 2.2). Following that, the topic marches on to characteristics of sewage flow at sewer upstream. Sewage flow at sewer downstream is briefly presented first to make a comparison (Section 2.3). After that, sewage quantity, quality, and sewage flow pattern at sewer upstream are extensively reviewed (Section 2.4 and 2.5). Properties of sewage flow pattern at sewer upstream are given special focus in this section.

2.1 Sewer Process and In-sewer Purification

2.1.1 Sewer process

Sewer was designed as a physical tool to transport sewage, but it is also potentially a biological reactor to transform pollutants in sewage. Sewage quality, in terms of organic matter and nutrients, alter considerably during transportation in sewer. This process is attributed to the activities of microorganisms in sewer sediments, in biofilm on sewer walls and in suspended solids in bulk sewage (14). Distribution of microorganisms in a gravity sewer is provided in **Fig 2**.

The exploration of microbial and chemical reactions in sewer, or sewer processes can be dated back to 1970s. During that time, the focus was on alteration of sewage components during transportation, through in-situ measurement or batch experiment (20). From 1990s, research focus progressed towards building a conceptual framework for sewer processes. The conceptual framework of sewer processes focused on activities of heterotrophic microorganisms, majorly divided into aerobic process (21, 22) , anaerobic process (23, 24) , and anoxic process (25). Methodologies to examine these processes included in-situ measurement, batch experiment, and modeling. In addition, relative contribution from suspended biomass and biofilm to sewer processes was also examined by lab-scale experiment (26, 27).Transformation between particulate matter and soluble matter, due to hydrolysis and microbial anabolism, was also involved in this framework (15).

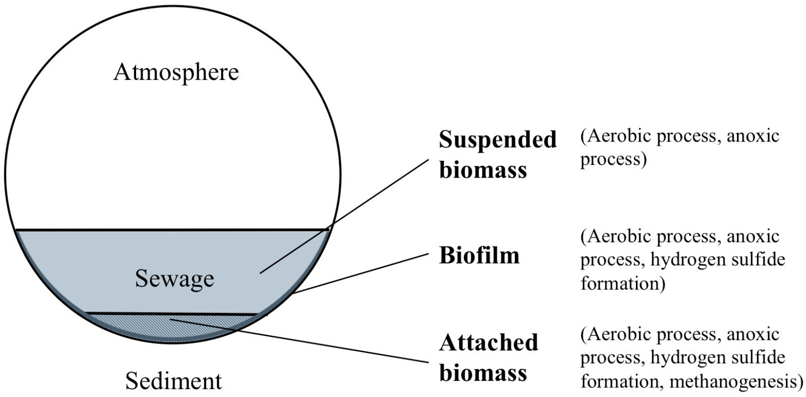


Fig 2 Microorganisms in a typical gravity sewer and relevant activities, adapted from (14)

A review of the conceptual framework of sewer processes was conducted by Hvitved-Jacobsen et al. (13). Later, this framework was further elaborated, incorporated into a sewer processes model, and calibrated with local parameters (14).

2.1.2 In-sewer purification

On the basis of structured understanding in sewer processes, several branches extended out during 2000s (**Fig 3**). One branch is controlling of sulfide hydrogen, which originates from anaerobic process in sewer and results in corrosion of sewer pipe (28). Another branch is to investigate behavior of fat, oil and greases (FOGs) in sewer, in order to control sewer blockage (29, 30). Moreover, the concept of actively utilizing sewer processes for pollutant degradation emerges as in-sewer purification (13). In-sewer purification is closely related with some specific aspects of sewer processes, and they are summarized as below:

1) In gravity sewer, heterotrophic microbial activity under aerobic condition is the dominating process for organic matter removal, with oxygen supply being a limiting factor.

2) In gravity sewer, biofilm typically plays a more important role than suspended biomass, and role of biofilm is more pronounced in sewer with smaller diameter.

3) HRT of sewage in sewer is usually comparable to that at WWTP, while food to microorganism ratio (F/M ratio) is usually much higher than F/M ratio at WWTP.

To move further in the branch of in-sewer purification, quantification of pollutants degradation under local sewer condition is desired. For this objective, approaches comprised in-situ measurement (31-36), operation of lab-scale pipe system (37-40), and batch experiments with raw sewage or synthetic sewage (41, 42). The emphasis was on organic matter removal (31, 32, 34, 35, 37-39, 41-43), nitrogen removal (32, 38, 39, 43) and oxygen consumption (31, 33, 34), while dynamics of microbial functional group was occasionally examined as well (43). With deeper understanding in quantified perspective, localized sewer models were proposed to evaluate and predict effect of in-sewer purification (34-37, 39-41, 44, 45).

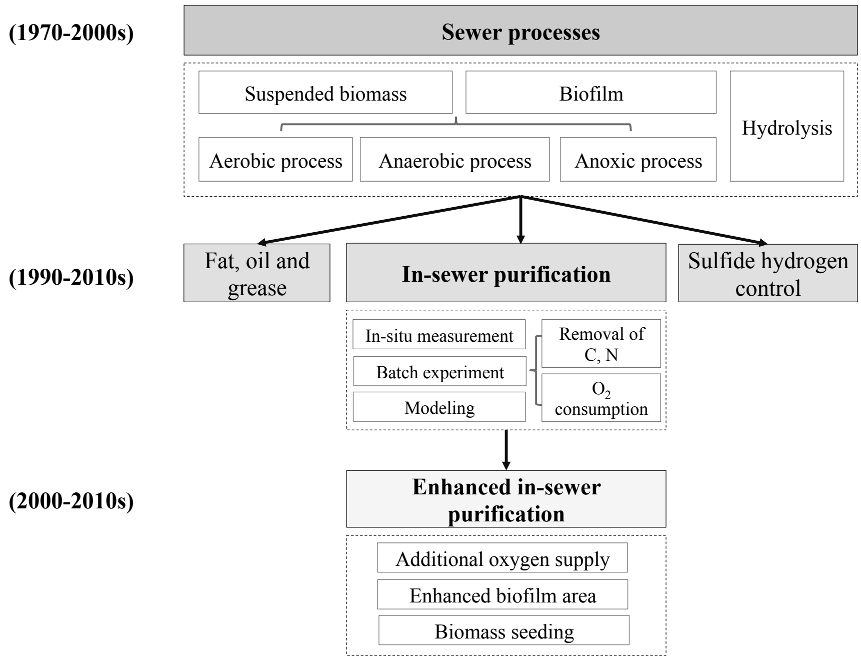


Fig 3 A timeline of study on sewer processes and related branches

In-sewer purification can function as a supplement or substitute of traditional WWTP. In-sewer purification contributes to reduce energy and chemical consumption for sewage treatment, together with the reduction of capital investment for WWTP. These advantages are expected to increase sustainability for current wastewater management system, as well as transit into a new wastewater management paradigm.

2.1.3 Enhanced in-sewer purification

Capacity of natural in-sewer purification is limited compared to sewage volume, and possibilities to enhance in-sewer purification are pursued. Strategies to enhance in-sewer purification consist of additional oxygen supply, increase of biofilm area and biomass seeding (14-16, 46). For instance, Marjaka et al. immobilized microorganisms as biofilm by installing porous ceramic material in sewer, and observed TOC removal, nitrification and denitrification (47). Tanji et al. installed six different concrete blocks in sewer, finding out the block made of wet-concrete with largest hole enhanced in-sewer purification most (48). Coulibaly et al. tested bio-augmentation with waste biomass from fermentation industries in sewer, which elevated chemical oxygen demand (COD) removal rate (49).

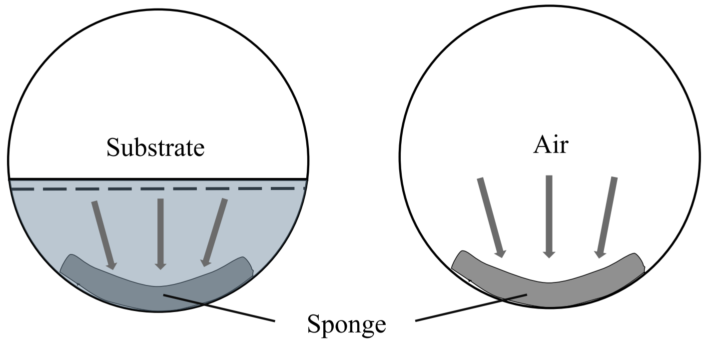


Fig 4 ICOP applied in sewer pipe as enhanced in-sewer purification

In a more recent study of Shoji et al., a double-layer pipe was utilized to enhance in-sewer purification, with upper layer to secure sewage transportation and lower layer to enhance self-purification (17). Sponge media installed in the lower layer provides habitat for microorganisms. When sewage flow is low, sewage runs only on the upper layer and the lower layer is kept dry, and when sewage flow is high, sewage spills from upper layer to sponge in the lower layer. Oxygen is supplied to microorganisms in two ways: one is the enhancement of aeration when sewage falls from upper layer to lower layer, and the other is the exposure of sponge media with air when sewage flow is low. Microorganisms living in the sponge media are intermittently exposed with sewage and air, which process is termed as intermittent contact oxidation process (ICOP). While double-layer structure ensured oxygen supply by two mechanisms (18), the technology is feasible for high-flow sewer. However, for low-flow sewer, double-layer structure is not as effective because sewage will run mostly on the upper layer only. For such sewer, placing sponge media at the bottom of sewer may be more feasible because oxygen can be supplied to microorganisms by ICOP if the flow is intermittent (**Fig 4**).

2.2 Sewer Upstream

Sewer upstream is defined as an aggregation of house sewer and lateral sewer. House sewer is the small pipe leading from households to public sewers, and lateral sewer is the sewer receiving sewage only from house sewer (19). Sewer upstream is therefore characterized by low-flow sewers. In comparison, sewer downstream refers to the main sewer line connecting lateral sewers and WWTP. An illustration of sewer upstream in a sewer network is provided in **Fig 5**.

Application of in-sewer purification to sewer upstream is worth to e seriously explored because of its length. Although lengths for each section of pipe at sewer upstream tend to be short, they make a surprisingly large fraction of whole sewer network (16). For instance, the length of house sewer and lateral sewer accounts for over 60% of whole sewer network in a city in Japan (50). In addition, HRT of sewage from sewer upstream is comparable to that at WWTP or even longer (16, 20, 39, 51). Further, sewage flow at sewer upstream is rich in substrate, especially easily biodegradable substrate (14, 22, 52).

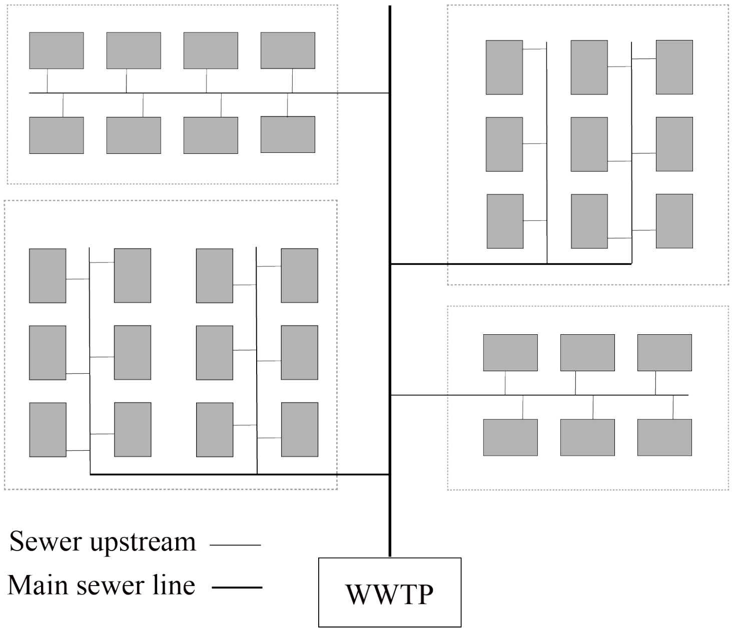


Fig 5 An illustration of sewer upstream

Given the performance of ICOP and characteristics of sewer upstream, applying ICOP at sewer upstream for enhanced in-sewer purification is proposed. Lipids in sewage put forward the concern of clogging in modified sewer, whereas ICOP demonstrates capability to degrade lipids with and without sewage flow (53). For deeper insight in performance of ICOP, knowledge in characteristics of sewage at sewer upstream is required.

2.3 Sewage Quantity, Quality and Flow Pattern at Sewer Downstream

Characteristics of sewage flow at sewer downstream are already well investigated and widely known, because they are essential for design and operation of WWTP. However, to better understand the characteristics of sewage flow at sewer upstream, reviewing them at sewer downstream is helpful. Therefore, an overview of sewage quantity, quality and sewage flow pattern at sewer downstream is provided in this section.

At sewer downstream, sewage quantity is usually examined as daily discharge per capita. A global design value for sewage quantity is 200 L/(cap·d) (54). Provided daily discharge per capita and size of population to be served, daily sewage flow into WWTP can be estimated (16).

As for sewage quality, domestic sewage of medium strength is 500 mg/L in COD, 200 mg/L in biological oxygen demand (BOD), 200 mg/L in total suspended solids (TSS), 35 mg/L in total nitrogen (TN) and 5 mg/L in total phosphorous (TP) (4, 55). On the basis of designed sewage flow and sewage quality, sewage pollutant load for WWTP is determined (4).

A typical sewage flow pattern at sewer downstream is provided in **Fig 6**. As an aggregation of sewage from a large user group, downstream sewage flow pattern generally displays a continuous 2-peak diurnal curve. The first peak occurs in the morning (7-9 am) when people get up, perform sanitary activities and cook breakfast. The second peak is noticed in the evening (18-22 pm), when most people return home from work, prepare dinner, clean rooms and perform sanitary activities. Between the two peaks there is a lower mid-day flow (12-16 pm), resulting from activities from households, schools and offices. At midnight (2-5 am) sewage flow is the lowest, deriving from people who stay up late.

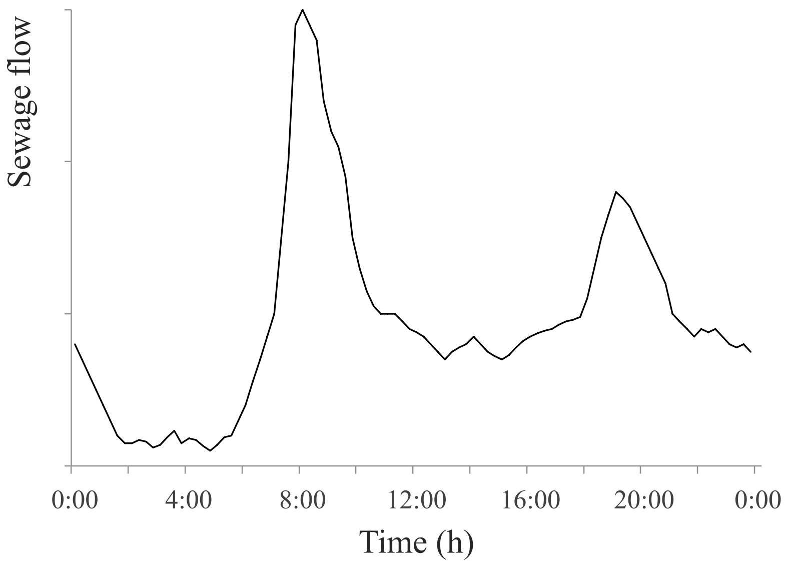


Fig 6 A typical sewage flow pattern at sewer downstream, qualitative, adapted from (56)

Variation in sewage flow pattern can be quantitatively described with peak factor, defined as ratio of peak flow to average flow. Peak factor decreases from upstream to downstream in a sewer network (16, 52, 57, 58). A typical hourly peak factor for medium or large WWTP is 1.5-1.9 (4), whereas Butler et al. reported for 100 households in England hourly peak factor is 3.48 (59). Likewise, Beal and Stewart found that hourly peak factor is 3.3 for 230 households (60). Similarly, hourly peak factor in Japan is 1.3-1.8 for medium and large cities, and more than 2 for small cities (61).

2.4 Sewage Quantity & Quality at Sewer Upstream

Opposite to sewer downstream, attention towards sewage at sewer upstream is limited but at the same time essential for application of in-sewer purification. Sewage quantity and quality at sewer upstream are hard to be neglected. For clear comprehension of these factors, source of sewage at sewer upstream has to be clarified first.

2.4.1 Household appliances

At sewer upstream, sewage derives directly from uses of household appliances (56), typically including toilet, shower, bath, hand basin, kitchen sink, and laundry (**Fig 7**). Sewage from toilet is termed as black water, and sewage from all other appliances is termed as gray water (62).

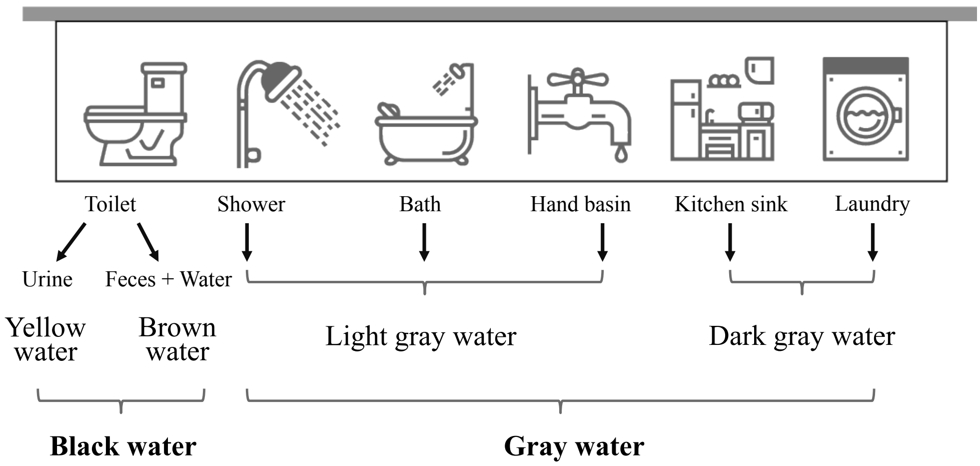


Fig 7 Household appliances and classification of sewage at sewer upstream

For further classification, black water is divided into yellow water (urine) and brown water (feces and water) (62). Gray water is divided into light gray water (sewage from shower, bath and hand basin) and dark gray water (sewage from kitchen sink and laundry) (63). Black water is usually much more polluted than gray water, and dark gray water is more concentrated than light gray water.

2.4.2 Sewage quantity and quality from household appliances

Quantity of sewage from each household appliance, in terms of daily discharge per capita, is summarized in **Table 1**. Total sewage quantity ranged from 102 to 275 L/(cap·d) in this review, suggesting sewage discharge varies substantially among countries. For sewage quantity from each household appliance, large discrepancy as much as 5 times is noticed as well. Total sewage quantity is sometimes higher than the sum of sewage quantity from each appliance, because sewage from other sources such as dishwasher is omitted.

Table 1 Quantity of sewage from each appliance [Unit: L/(cap·d)]

Appliance	**Source**						
	(54) Japan	(64) Portugal	(59) UK	(65) U.S.	(66)[1] U.S.	(67) U.S.	(68) N.A.[4]
Total	200	143	102	174	269	222	275
Toilet	50	21	31	42	70	54	78
Hand basin	30	17	13	38[2]	41[2]	42[2]	31[2]
Bath	50[3]	37[3]		5	5	6	29
Shower			28	45	44	42	55
Kitchen sink	30	56	13				
Laundry	40	12	17	44	57	36	63

[1] Data of standard new home referred to.
[2] Mixture of sewage from hand basin and kitchen sink.
[3] Mixture of sewage from shower and bath.
[4] Not available.

Quality of sewage in total, black water, gray water, and sewage from each household appliance are displayed in **Table 2**. Indicators for sewage quality contain COD, BOD, TSS, TN, TP and pH. Sewage quality fluctuates highly among different studies. Even for single study, sewage quality from different appliance is also scattered. Black water is the most contaminated among all sources. Black water is 2-3 times more concentrated in organic matter and nutrients than sewage in total, and is nearly 10 times richer in nutrients than gray water. As for gray water, dark gray water is more polluted compared to light gray water, especially in terms of organic matter, TSS and TP. This may be attributed to high level of food waste and detergents inside dark gray water.

Table 2 Quality of sewage from each appliance

Appliance	Source	Country	COD (mg/L)	BOD (mg/L)	TSS (mg/L)	TN (mg/L)	TP (mg/L)	pH
Total	(59)	Malta		527		25	15	
	(59)	UK		492		23	14	
	(4)	U.S.	508	200	195	35	5.6	
	(14)	N.A.[2]	500	250	300	40	8	
Black	(59)	Malta		682		69	11	
	(59)	UK		653		66	10	
	(69)	Turkey	1225	338	625	180	25	8
Gray	(70)	France	399	240	125	9.5	0.42	7.58
	(69)	Turkey	295	111	63	7.4	1.6	7.2
	(71)	Vietnam	400-700	250-500		10-17	3-8	6.9-8
	(72)	N.A.[2]	350-783	205-449	228	6.7-22	0.4-8.2	
Dark gray water								
Kitchen sink	(73)	Greece	775		299	4	0.4	6.72
	(74)	Jordan	8071	1850	1180	25.9	4.3	6.83
	(59)	Malta		669		4.01	12	
	(59)	UK		756		4.58	14	
	(75)	UK	1079		235	6.1	26	
	(76)	UK	936	536		5.05	15.6	
	(63)	N.A.[2]	58-1340	40.8-890	134-625	6.44	0.69	6.5-7.7
Laundry	(74)	Jordan	2500	1266	760	2.8	9	9.6
	(75)	UK	1815		165	4	21	
	(76)	UK	725	472		12.3	101	8.1
	(63)	N.A.[2]	58-1339	44.3-462	188-315	14.28	51.58	8.3-9.3
Light gray water								
Bath	(75)	UK	210		54	5.3	5.3	
	(63)	N.A.[2]	230-367	129-173	58-78	6.6		7.1-7.6
Shower	(77)[1]	German	100-200	50-100		5-10	0.2-0.6	
	(73)[1]	Greece	399		63	8.4	0.4	7.22
	(74)	Jordan	537	120	150	2.4	1.2	7.15
	(59)[1]	Malta		274		1.99	0.98	
	(63)	N.A.[2]	77-645	40.2-424	89-353	8.7-10.92	1.12	7.3-7.5
	(59)[1]	UK		250		1.86	0.89	
	(75)	UK	501		200	7.5	19.2	
	(76)[1]	UK	424	216		2.46	1.63	7.6
Hand basin	(73)	Greece	335		61	2.6	0.7	7.07
	(59)	Malta		215		0.25	44	
	(63)	N.A.[2]	386-587	155-205	153-259	10.4		7-7.3
	(59)	UK		148		0.86	30	
	(75)	UK	298		181	6.3	13.3	
	(76)	UK	433	252		0.87	45.5	8.1

[1] Mixture of sewage from shower and bath.
[2] Not available.

These data indicate that quantity and quality of sewage at sewer upstream are highly varied. This variability can be attributed to local water availability, local climate, season of year, weekday or weekend, socio-economic factor, water conservation measures, etc. Hereby, exact value of sewage quantity and quality can still be higher or lower than this review depending on local situation.

2.4.3 Relative contribution from household appliances

Examining relative contribution from each household appliance to sewage quantity and quality is also of interest. For sewage quantity, percentage of each appliance is calculated according to sewage quantity from each household appliance and total sewage quantity (**Table 3**). Quantity of gray water is dominating, that is, 46-84% of total sewage quantity. On the other hand, share of black water is much smaller (14-31%). Due to leaking and sewage from other sources, share of black water and gray water does not equal 100% in some studies.

Table 3 Share of each household appliance in sewage quantity (%)

Appliance	Source									
	(78) India	(54) Japan	(64) Portugal	(79) Spain	(59) UK	(65)[1] U.S.	(66) U.S.	(67) U.S.	(80) N.A.[4]	(68) N.A.[4]
Black water	30	25	14	22	30	20	27	24	31	28
Gray water	70	75	84	69	69	60	57	59	46	64
Hand basin	5	15	12	39[2]	12	18	16[2]	19[2]	9	12[2]
Bath	34[3]	25[3]				2	2	3	15	10
Shower			26[3]	20	28	20	17	20	5	20
Kitchen sink	12	15	38		13				15	
Laundry	19	20	8	10	16	20	22	17	2	22

[1] Data of standard new home referred to.
[2] Mixture of sewage from hand basin and kitchen sink.
[3] Mixture of sewage from shower and bath.
[4] Not available.

Relative contribution to sewage quality is expressed as daily pollutant discharge (mg/d). Butler et al. confirmed the decisive role of black water in daily BOD and NO_3^- discharge (59). Similarly, Meinzinger et al. reported black water accounts for 60% COD, 60% TSS, 80% TN and 75% TP discharge, far exceeding contribution of gray water (72). Almeida et al. found that black water represents the highest contribution to all metrics except for nitrate (75). Furthermore, black water is a major source of solids of domestic sewage (75). Still, in general black water is a major contributor to TN and TP, but gray water takes more responsibility to organic matter and solids (61).

These observations imply that at sewer upstream, black water is highly concentrated with smaller quantity, whereas gray water is slightly polluted with dominating quantity.

2.5 Sewage Flow Pattern At Sewer Upstream

Apart from sewage quantity and quality, sewage flow pattern is another influencing factor of in-sewer purification. Sewage flow pattern at sewer upstream is usually hard to measure directly. Thus, an indirect approach is employed to investigate household appliances usage by questionnaire or interpretation of water use data (81). It should be noted that water use data is usually transformed into sewage emission with a return factor from 0.6 to 0.95 (16), whereas in this study, this return factor is omitted.

2.5.1 Frequency, duration and water flow rate of household appliance usage

For the purpose of describing household appliance usage, frequency, duration, and water flow rate are selected as indicators (**Table 4**). Frequencies of appliance usage are highly scattered. Toilets, hand basin and kitchen sink are operated 2-6 times/(cap·d), whereas shower is used less than once a day, and bath and laundry are even more rarely applied. Likewise, duration of appliance usage fluctuates substantially. Water from toilet, hand basin and kitchen sink flows into sewer for less than 1 min, on the other hand, water flow from bath, shower and laundry lasts up to several minutes. Despite limited data of water flow rate, inconstancy can be noticed among appliances and even for single appliance. Water flow rate from shower, bath and laundry is higher, while water flow rate from toilet, hand basin, and kitchen sink is comparatively lower. Moreover, for toilet, hand basin, and kitchen sink, significant difference can be found on water flow rates.

Table 4 Frequency, duration and rate of water flow rate of household appliance usage

Appliance	Source	Country	Frequency [uses/(cap.d)]	Duration (s)	Flow rate (L/min)	Appliance	Source	Country	Frequency [uses/(cap.d)]	Duration (s)	Flow rate (L/min)
Toilet	(82)	Australia	4.3			Shower	(82)	Australia	0.81	456	9.1
	(83)	Maltese	2.9				(83)	Maltese	0.46		
	(84)	Netherland	6	144	2.52		(84)	Netherland	0.7	510	8.5
	(64)	Portugal	2.7				(79)	Spain			8.2
	(79)	Spain			6.7		(85)	UK	0.19	530	
	(85)	UK	3.7	9			(66)	U.S.	0.75[1]		
	(66)	U.S.	5.05				(68)	N.A.[4]	0.75	400	7-15
	(68)	N.A.[4]	4	30	0.33-0.86						
Hand basin	(82)	Australia		21[2]	4[2]						
	(83)	Maltese	3.37			Kitchen sink	(83)	Maltese	1.61		
	(84)	Netherland	4.1	40	2.52		(84)	Netherland	4.2	15-48	5-7.5
	(64)	Portugal	4				(64)	Portugal	3.7		
	(79)	Spain			5[2]		(85)	UK	2	53	
	(85)	UK	3.4	36							
	(68)	N.A.[4]	4.3	60	up to 15						
						Laundry	(82)	Australia	0.32		100[3]
Bath	(82)	Australia	0.61		75[3]		(83)	Maltese	0.19		
	(83)	Maltese	0.39				(64)	Portugal	0.3		
	(84)	Netherland	0.044	600	12		(79)	Spain			6.9
	(64)	Portugal	0.7				(85)	UK	0.15		
	(85)	UK	0.24	123			(66)	U.S.	0.37		
	(68)	N.A.[4]	0.25	300	0.38		(68)	N.A.[4]	0.63	504	0.2

[1] Mixture of sewage from shower and bath.
[2] Mixture of sewage from hand basin and kitchen sink.
[3].Liter per use.
[4] Not available.
.

Based on the statistics, properties of sewage flow at sewer upstream can be summarized. To start with, sewage flow is highly intermittent at sewer upstream. This is because upstream sewage is generated from appliance usage, frequencies of which are rather limited (no more than 20 times per day). Additionally, sewage flow from laundry is intrinsically stepwise, in that washing machine injects and discharges water at given stages (79, 86) . Hence, laundry activities solidify the intermittency at sewer upstream. Intervals between sewage flow are not fixed, generally longer during mid-night and mid-day and shorter during peak hours, which is explained by unevenly distributed appliance usage in one day (64, 66, 79, 85).

Time with sewage flow is extremely limited at sewer upstream. The period with sewage flow can be roughly estimated by multiplying appliance usage frequency by its duration, which is no more than 30 min per day. Likewise, Jacobsen et al. reported for 95% of time sewer upstream is under dry condition (14). Buchberger et al. proposed utilization factor of upstream sewer is quite low (87). Friedler and Butler also pointed out that zero use of household appliances is mostly observed on hourly basis (88). In short, dry condition prevails over wet condition at sewer upstream.

Sewage flow is hydraulically unstable at sewer upstream. This instability is reflected by scattered water flow rate from different appliances and even from single appliance. For the latter case, unsteady toilet flow can be explained by different discharging modes, like urine and feces. Large variation in flow from hand basin and kitchen sink is attributed to run to waste mode of these appliances (88). A similar opinion is that most variation in sewage flow rate occurs with use of random appliances, including hand basin, kitchen sink, bath and shower (87).

2.5.2 Sewage flow pattern at sewer upstream

From the use of household appliance, sewage flow pattern at sewerage upstream can be estimated, as sewage generated goes into sewer without delay. An example of the estimation is shown in **Fig 8**. This pattern applies to a household resided by people who work outside the home. In the morning and evening there are two peaks, when people prepare before going to work and returning home after work. During the daytime there is occasional sewage flow, considering sometimes people stay at home or appliances function automatically. And at midnight there is hardly sewage flow.

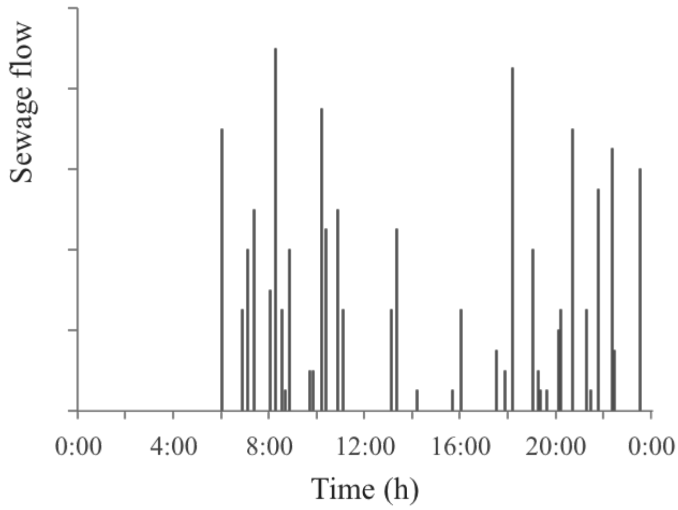


Fig 8 A typical sewage flow pattern at sewer upstream, adapted from (68)

To sum up, sewage flow pattern at upstream is intermittent, with prevailing dry condition, instable hydrological condition and larger peak factor. On the other hand, sewage flow pattern at downstream is continuous, with less variation in flow rate and smaller peak factor. Several explanations account for these differences. One is size of users being served, because larger user group at sewer downstream indicates higher frequencies of emission, which generates pseudo-continuous flow (4). Another one is dampening effect of sewer, or the hydraulic equalization of flow in sewer from upstream to downstream (4, 16, 81). What's more, different time resolution applied for recording the flow pattern exacerbates the discrepancy between sewer upstream and downstream (85, 89).

2.6 Chapter Summary

In this chapter, a history of in-sewer purification and characteristics of sewer upstream are reviewed. The following conclusions are drawn from each section:

1) Chemical and biological processes in sewer are termed as sewer processes. The concept of actively utilizing sewer processes for sewage treatment emerges as in-sewer purification.

2) Possibilities exist to enhance natural in-sewer purification. The ICOP can be applied in sewer to enhance in-sewer purification, by installing sponge media to retain microorganisms with intermittent sewage flow.

3) Sewer upstream, defined as an aggregation of house sewer and lateral sewer, is proposed for application of in-sewer purification as well as ICOP.

4) Sewage at upstream derives directly from usage of household appliances, including toilet, shower, bath, hand basin, kitchen sink, and laundry. Domestic sewage is commonly divided into black water and gray water.

5) Quantity and quality of sewage from different appliances are highly varied. Black water is highly concentrated with limited quantity, whereas gray water is slightly polluted with dominating quantity.

6) Sewage flow at sewer upstream is characterized by varied intermittency, prevailing dry condition and hydraulic instability. Peak factor of sewage flow at upstream is larger than that at downstream.

CHAPTER 3 INTERMITTENT CONTACT OXIDATION PROCESS UNDER SEWER UPSTREAM CONDITION

With the understanding in sewage flow at sewer upstream, the objective of this chapter is to explore performance of ICOP under simulated sewer upstream condition. This objective is achieved by assembling lab-scale ICOP reactor, operating it under a simplified flow pattern, and monitoring organic matter removal efficiency. This chapter is organized as follows: first, materials and methods needed for the experiment are described in detail (Section 3.1). Correspondingly, results are displayed as organic matter removal efficiency, headspace oxygen consumption, oxygen balance, influence of temperature, and variation of PHA (Section 3.2). Moving further with the results, a more general discussion is provided, focusing on mechanisms of organic matter removal, potential performance of ICOP, and reflections on experimental design (Section 3.3).

3.1 Materials and Methods

3.1.1 Experimental setup

Two lab-scale airtight ICOP reactors named R_1 and R_2 were fabricated. Each ICOP reactor consisted of a rectangular pipe (50 cm long, 7 cm wide and 5 cm deep, inner volume of which 1.75 L, made of 0.5 cm thick transparent polyvinylchloride plastic plates), a piece of sponge (45 cm long, 7 cm wide and 1 cm deep, 0.32 L in volume, manufactured by Sekisui Chemical Co., Tokyo, Japan), an oxygen sensor (Grove Oxygen Sensor, SEED Technology, Shenzhen, China). Feed water was supplied from a synthetic sewage tank and a tap water tank, and the discharged water was collected by a receiving water tank (**Fig 9**).

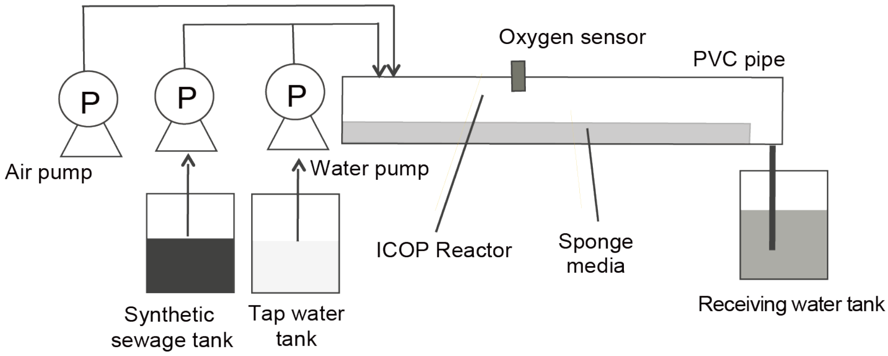


Fig 9 Experimental setup of ICOP reactor

To each ICOP reactor, synthetic sewage and tap water were introduced following a simplified flow pattern (**Fig 10**). In each cycle, firstly 50 mL synthetic sewage was introduced to the reactor (720 mL/min for 4 s). Then, after an idle time without flow for T_1, 1 L tap water was flown at a rate of 333 mL/min for 3 min. After that, the reactor was kept idle for T_2. The feed volume of synthetic sewage was set based on volume of sponge, so that synthetic sewage feed could be fully absorbed by the sponge without being discharged immediately. Similarly, the feed volume of tap water was set large enough to wash out absorbed sewage entirely. To supply synthetic sewage and tap water, peristaltic pumps (Masterflex pump 7518-10, Cole-Parmer Instrument Co., Vernon Hills, Illinois) were applied. Before initiating the next cycle, an air pump (APN-085V-1, Iwaki Co. Ltd., Tokyo, Japan) was operated to refresh air in the reactor (5 L/min for 1.5 min).

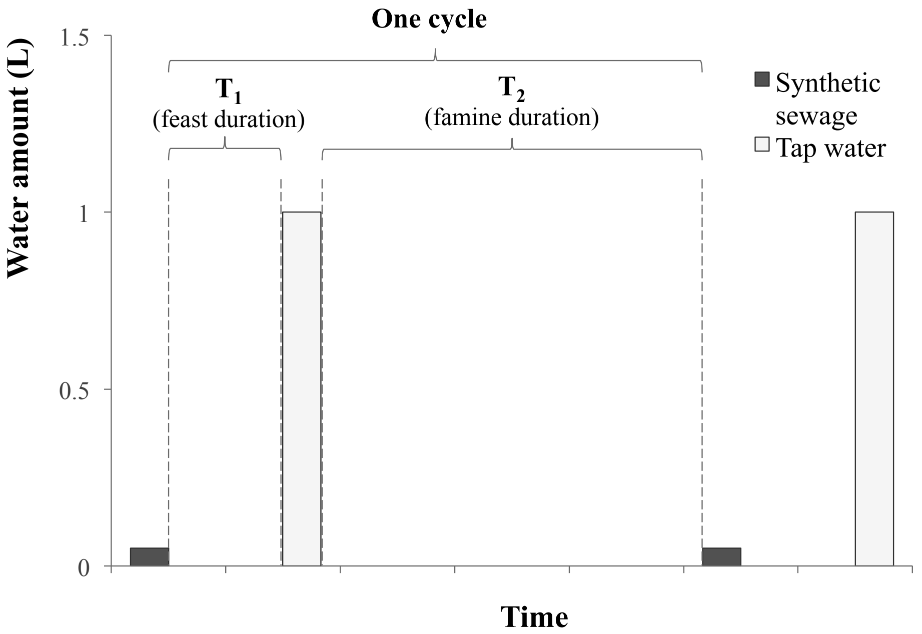


Fig 10 Proposal for simplified upstream sewage flow pattern

Each 1 L synthetic sewage contained: 4.52 g $CH_3COONa{\cdot}3H_2O$, 1.32 g peptone, 0.44 g yeast extract, 0.44 g KCl, 0.264 g $CaCl_2{\cdot}2H_2O$, 1 g NH_4Cl, 2.2 g $MgSO_4{\cdot}7H_2O$, 0.72 g K_2HPO4, and 3 mL trace metal solution (estimated TOC = 1988 mg/L). Trace metal solution was prepared according to Smolders et al. (90). All chemicals were obtained from FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan. Synthetic sewage and tap water were replaced every day.

The oxygen sensor of each ICOP reactor was connected to a data logger (Funduino Uno R3, Tosa-Denshi, Tosa) in order to monitor consumption of oxygen in headspace of the reactor. To isolate headspace gas inside the reactor from ambient air, the reactors were made airtight and the outlet was water-sealed by water in the receiving water tank.

The reactors were inoculated with sponge from other ICOP reactors, which had been operated at a municipal wastewater treatment plant for about one year. After inoculation, reactors were acclimatized under feast-famine flow pattern (T1 = 30 min and T2 = 4 h). Acclimatization of R_1 was started about 1 month earlier than that of R_2, and after another 1-month acclimatization, performance of R_1 and R_2 were similar.

3.1.2 Simplified flow pattern

After acclimatization, Experiment 1 and Experiment 2 were carried out with the aim to study influence of T_1 and T_2 respectively. In Experiment 1, T_1 was set at 5, 10, 15, 30, 60 and 120 min, and T_2 was set constant at 240 min. On the other hand, in Experiment 2, T_1 was set constant at 30 min, and T_2 was set at 2, 4, 8 and 24 h. There were 9 combinations of T_1 and T_2 in total. Beginning from $T_1 = 5$ min and $T_2 = 4$ h, Experiment 1 with different T_1 was conducted, and then Experiment 2 with different T_2 was performed. For each combination of T_1 and T_2, at least 5 cycles were monitored before shifting into the next combination. To confirm that organic matter removal was a result of microbial activities, an experiment using sponge without biomass was also performed for 5 cycles, with $T_1 = 5$ min and $T_2 = 4$ h. During the whole experiment, R_1 and R_2 were run in parallel, and ambient temperature was maintained at 25 °C.

This simplified flow pattern reproduces the nature of upstream sewage flow in the following aspects: First, introduction of synthetic sewage and tap water reflects fluctuation in sewage quantity and quality: highly concentrated synthetic sewage simulates black water with small volume and tap water simulates weak sewage with large volume. Then, time without water flow, T_1 and T_2 represent for intermittency of sewage flow. Besides, long T_2 functions as prevailing dry condition. Finally, synthetic sewage and tap water are supplied at different speed, to manifest fluctuation in sewage flow rate.

The T_1 and T_2 actually created a feast-famine condition for microorganisms in sewer, thereby, the terms feast duration and famine duration are sometimes used as the same meaning of T_1 and T_2.

3.1.3 Monitoring of cycles

Monitoring of a feast-famine cycle was performed as follows. First, the receiving water tank was emptied and washed, and 1 L tap water was placed inside to isolate headspace gas in the reactor from ambient air. Then, a cycle as explained in the previous section was started.

The synthetic sewage sample was taken from synthetic sewage tank, and treated water sample was collected from receiving water tank after tap water flow ended. The treated water sample was a mixture of the discharge from the feeding of synthetic sewage and tap water.Each sample was measured for total organic carbon (TOC) usually within 3 h after collection, otherwise it was kept under 4 °C with pH adjusted to 2.5 until analysis. The measurement of TOC was performed with a TOC analyzer (TOC-V, Shimadzu). Tap water sample was collected from tap water tank and measured in the same manner, TOC of which was around 1 mg/L.

For one cycle, loaded TOC mass (mg) and outlet TOC mass (mg) of each reactor were calculated as follows:

$$\text{Loaded TOC mass} = (TOC_{syn} - TOC_{tap}) \times V_{syn} \quad (1)$$

$$\text{Outlet TOC mass} = (TOC_{treated} - TOC_{tap}) \times V_{total} \quad (2)$$

where TOC_{syn}, $TOC_{treated}$ and TOC_{tap} are TOC concentrations of synthetic sewage, treated water and tap water, respectively, V_{syn} is the volume of synthetic sewage (0.05L), and V_{total} is the sum of volumes of tap water initially preserved in receiving tank (1 L), synthetic sewage (0.05L), and tap water flown after T_1 (1 L). On the basis of loaded and outlet TOC masses, TOC removal efficiency was computed as a ratio of removed TOC mass to loaded TOC mass.

Headspace oxygen consumption rate (HOCR) [$mgO_2/(h \cdot L\text{-sponge})$] was calculated as below:

$$HOCR = M_{O2} \times (V_{reactor} - V_{sponge}) \times \Delta O_2 / (\Delta T \times Vm_{O2} \times V_{sponge}) \quad (3)$$

where ΔO_2 is the reduction of oxygen as partial pressure against atmospheric pressure in the given period, ΔT is the duration of the period, Vm_{O2} is the volume of one mole ideal gas at 25 °C under atmospheric pressure (24 L/mol), and M_{O2} is the mass of one mole of oxygen (32 g/mol). Time intervals ΔT for HOCR calculation were 5 min for the first 30 min, 10 min during 30-120 min, 30 min during 120-240 min, and 60 min after 240 min in a cycle.

Further, headspace oxygen consumption (HOC) [$mgO_2/(L\text{-sponge})$] during a period of time within a cycle was calculated by equation (4):

$$HOC = M_{O2} \times (V_{reactor} - V_{sponge}) \times \Delta O_2 / (Vm_{O2} \times V_{sponge}) \quad (4)$$

To convert TOC removal into chemical oxygen demand (COD) removal, a factor of 2.5 was multiplied to TOC removal. The value of the factor is originated from chemical constituents of synthetic sewage where acetate was the major carbon source.

3.1.4 Effect of temperature

The influence of temperature on performance of ICOP was tested as below. After accomplishing Experiment 1 and Experiment 2 in section 3.1.2, the reactors were operated continuously under the simplified pattern for 2 months until winter came. Then, Experiment 1 was repeated without strict temperature control, average ambient temperature during which time was around 15 °C. The temperature was measured with a temperature sensor connected to the data logger (thermistor 203AT-11, Semitec, Tokyo, Japan). This experiment under low temperature was termed as Experiment 3. During Experiment 3, monitoring of cycles was performed in the same manner as described in Section 3.1.3.

3.1.5 Polyhydroxyalkanoate (PHA) analysis

The measurement of PHA inside microorganisms in sponge media was conducted according to Satoh et al. (91). To fix microbial activities, the sponge sample was immediately submerged in 2N NaOH solution and adequately squeezed, so that the sponge is saturated with NaOH solution. At the timing of PHA analysis, both reactors had been operated under the simplified pattern for around 9 months, and worms (larvae of the filter flies) and small bugs were noticed in the reactors.

Three batches of experiment (one run for each batch) were performed, with T_1 = 5, 30, 120 min and T_2 = 240 min. For each batch of experiment, 3 samples were taken from upper, middle and lower part of the sponge each time of sampling from the upstream to the downstream, volume of which were around 1 cm^3. Timing for sampling was 1, 5, 30, 60, 120, 240 min when T_1 = 5 min, 5, 10, 30, 60, 90, 150, 270 min when T_1 = 30 min, and 5, 10, 30, 60, 120, 150, 180, 240, 360 min when T_1 = 120 min. To determine the volume of sponge sample, sponge samples were washed, dried and weighed after PHA extraction, and volume of sample was calculated as the weight divided by density of the sponge (29.5 g/L). During this experiment, the reactors were open without lids for the convenience of sampling. Room temperature was not strictly maintained but was around 22 °C.

Amount of PHA (mg/L-sponge) was calculated as follows:

$$PHA = (A \times C_{standard} \times V_{solution} \times \rho_{sponge}) / (M_{sponge} \times A_{standard}) \quad (5)$$

where A is peak area of PHA, $C_{standard}$ is the concentration of standard PHA solution (100 mg/L), $V_{solution}$ is the volume of PHA sample solution (14 mL), ρ_{sponge} is density of sponge, M_{sponge} is the weight of sponge sample, and $A_{standard}$ is peak area of standard PHA solution (4391617).

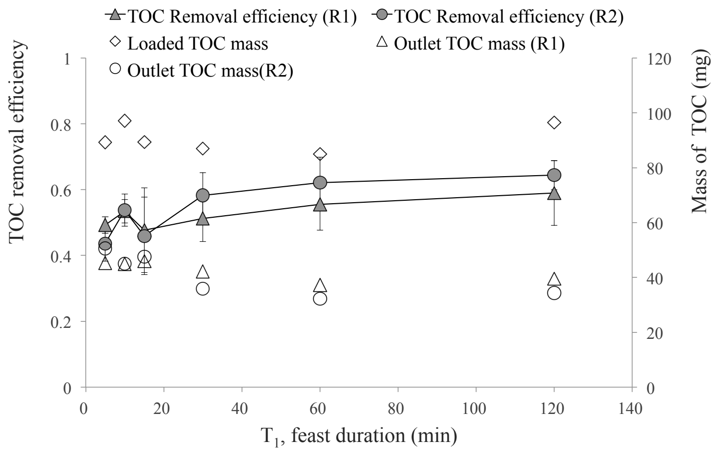
3.2 Results

3.2.1 TOC removal efficiency

During 3-month operation, sponge in both reactors appeared brownish, and a thin layer of biofilm grew over sponge surface. Except for the development of thin biofilm on the surface of the sponge, there was no obvious sludge generation on the sponge.

In Experiment 1, TOC removal efficiency under different feast duration (T_1) was explored (**Fig 11** a). With feast duration rising from 5 to 120 min, TOC removal efficiency increased slightly from 45% to 60%. Even when feast duration was short (T_1 = 5,10 or 15 min), TOC removal efficiency stayed at around 50%. In order to confirm the removal of TOC with the shortest feast duration (T_1 = 5 min), a control experiment was undertaken using a sponge sheet without biomass. We observed no TOC removal with the sponge sheet without biomass, which indicates that organic matter removal within short feast duration was induced by microbial activities.

a)



b)

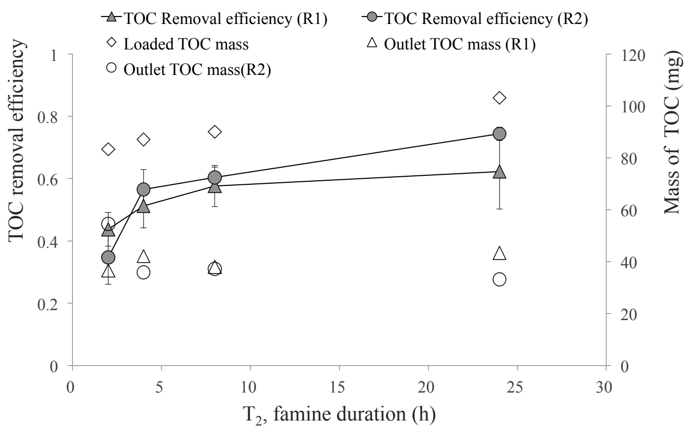


Fig 11 TOC removal efficiency, mass of loaded and outlet TOC, a): Experiment 1, T_1 varied while T_2 = 4 h, b): Experiment 2, T_2 varied while T_1 = 30 min, error bar: standard deviation of TOC removal efficiency, N = 5.

In Experiment 2, famine duration (T_2) and TOC removal efficiency were examined in a similar manner (**Fig 11** b). When T_2 was 2 h, TOC removal efficiency was rather low (40%). With T_2 changed from 4 to 24 h, TOC removal efficiency climbed up gently from 55% to 68%. Even when T_2 was 24 h, no obvious influence on system performance was noticed, which proves that ICOP is able to endure long famine duration. A 12-fold increase in T_2 (2 to 24 h) generated larger variation in TOC removal efficiency compared to the same increase in T_1 (10 to 120 min), implying organic matter removal depends more on famine duration length.

Overall, except for short famine duration, ICOP demonstrated stable organic matter removal efficiency under dynamic feast-famine condition, even for extremely short feast duration and long famine duration.

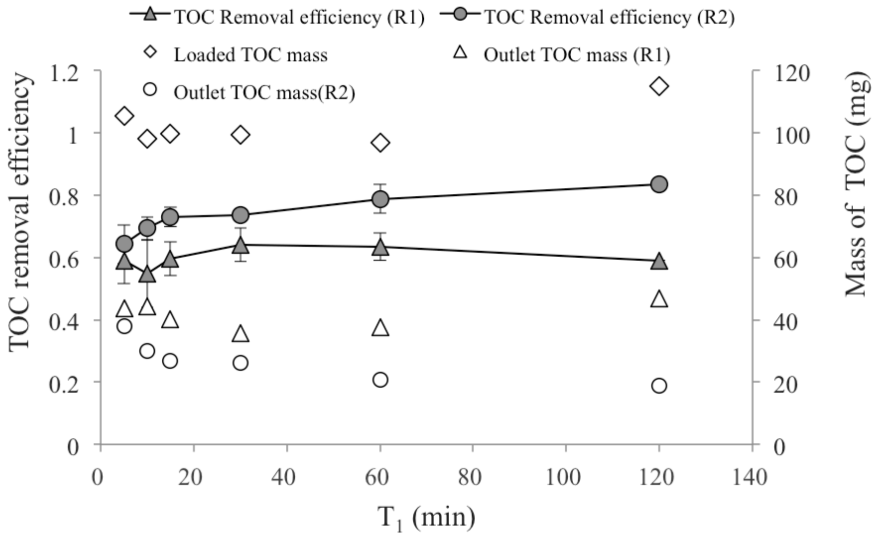


Fig 12 TOC removal efficiency, mass of loaded and outlet TOC (Experiment 3, T_1 varied while T_2 = 4h)

Before Experiment 3, worms and filter flies started to be noticed in the reactor. Detection of worms was earlier in R_2 than R_1. Average temperature was around 15 °C.

For Experiment 3, the relationship between TOC removal efficiency and feast duration (T_1) under low temperature was examined as well (**Fig 12**). TOC removal efficiency in Experiment 3 was higher than that in Experiment 1. With T_1 increased from 5 min to 120 min, TOC removal efficiency was 60-80%. Even under short T_1, TOC removal efficiency was as much as 70%. For all T_1 tested, TOC removal efficiency of R_2 exceeded that of R_1 by10-20%. Still, the general trend of TOC removal efficiency was rather stable to variation of feast duration.

3.2.2 Headspace oxygen consumption

An example profile of headspace oxygen concentration within a cycle is shown in **Fig 13**. Headspace oxygen concentration decreased rapidly at the beginning of feast duration, after a short period it went down more slowly, and during famine duration its variation became further moderate. Similar pattern was observed for all cycles.

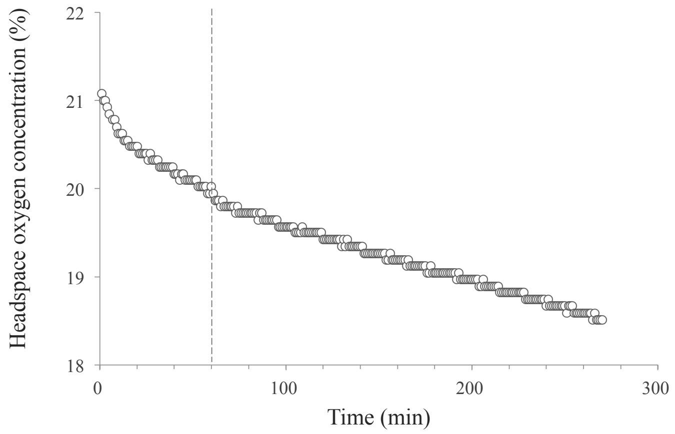


Fig 13 A case of headspace oxygen concentration variation within a cycle, $T_1 = 60$ min, $T_2 = 4$ h, dash line: beginning of T_2.

Reactors R_1 and R_2 demonstrated similar HOCR patterns for Experiment 1 and 2, among which 3 sets of results are shown in **Fig 14**. Three general phases are observable in HOCR patterns. Phase 1 refers to the first 5-10 min in feast duration, when HOCR demonstrated the peak value. A case of Phase 1 is 0-5 min in **Fig 14** (a). Phase 2 describes the period between Phase 1 and famine duration, when HOCR dropped to 1/2-1/3 of the peak value and then decreased more gently. Example of Phase 2 is 10-30 min in **Fig 14** (b), and this phase did not appear in **Fig 14** (a) because feast duration was too short. Phase 3 corresponds to famine duration, during which time HOCR went down further and stayed at low level. Phase 3 is illustrated by 120-300 min in **Fig 14** (c), when a slight but continuous decrease of HOCR was also noticed.

The HOCR pattern under lower temperature was also different from that in Experiment 1 and 2 (**Fig.15**). For Phase 1, the peak HOCR value was lower, almost half of HOCR under 25°C. For Phase 3, however, HOCR was higher. Discrepancy was also noticed between HOCR of R_1 and R_2. Compared to HOCR of R_1, HOCR of R_2 was lower during Phase 1 and higher during Phase 3, whereas in previous experiment the difference was not obvious. The smoother HOCR of R_2 could be attributed to development of a longer food chain in the reactor, with the existence of filter flies. In summary, under lower temperature the variation in HOCR pattern was much more moderate.

a)

b)

c)

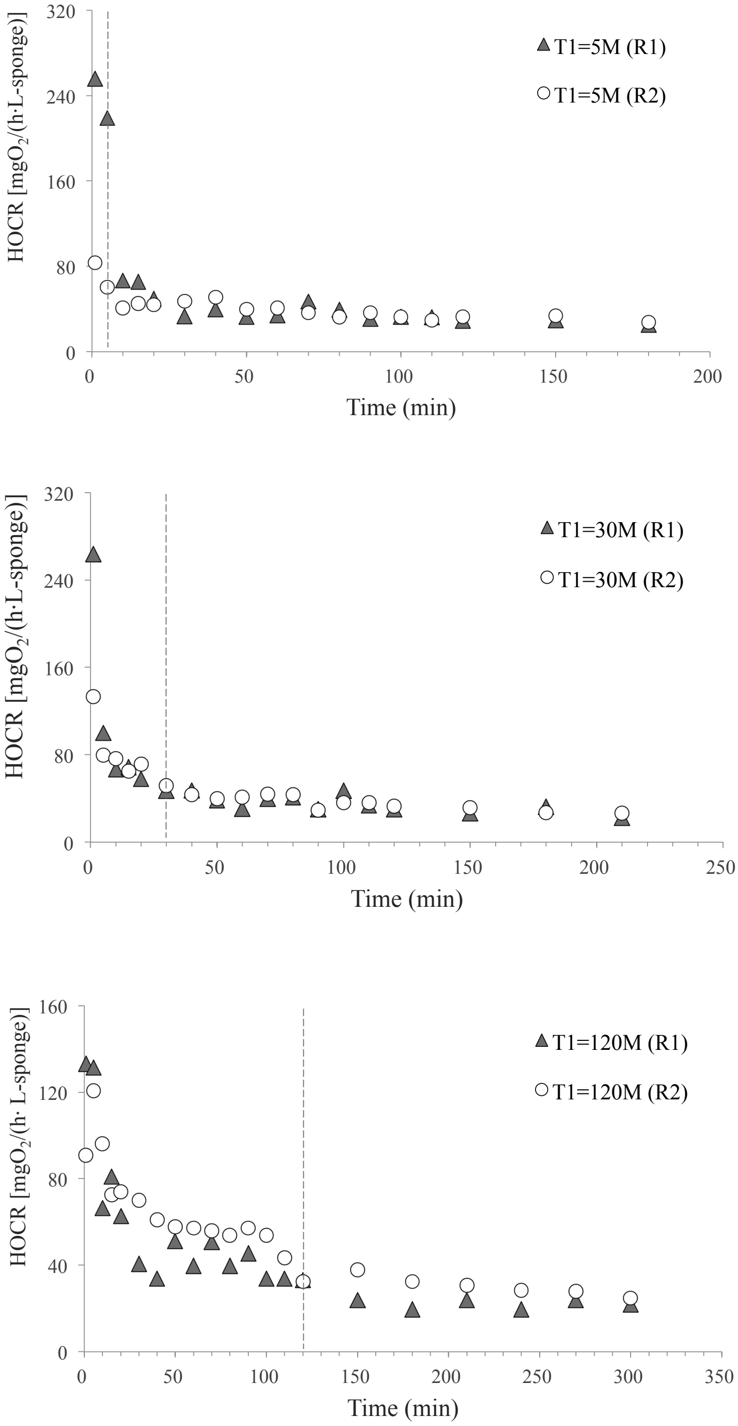


Fig 14 Variation of HOCR within a cycle, a): $T_1 = 5$ min, $T_2 = 4$ h; b): $T_1 = 30$ min, $T_2 = 4$ h; c): $T_1 = 120$ min, $T_2 = 4$ h, dash line: beginning of T_2.

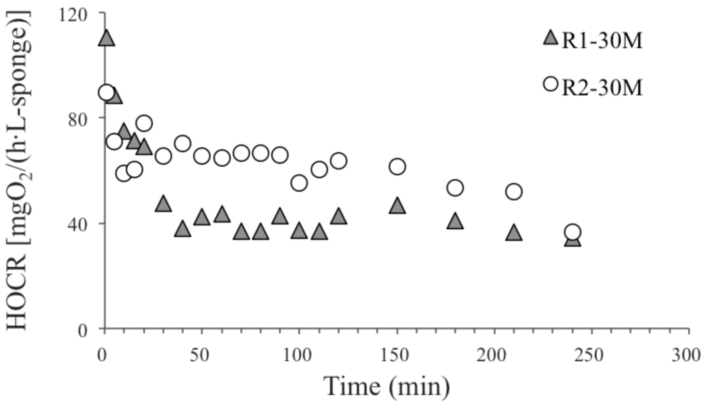


Fig 15 Variation of HOCR within a cycle, T_1 = 30 min, T_2 = 4h, ambient temperature: around 15°C

3.2.3 Oxygen balance

To examine the oxygen balance of a whole cycle, COD removal per volume sponge was estimated from TOC removal and compared with HOC in T_1 and T_2 for R_1 (**Fig 16**). For both experiments, COD removal exceeded the sum of HOC in T_1 and T_2. HOC in T_1 was less than 30% of COD removal, while HOC in T_2 was 21-65% of COD removal, signifying more oxygen consumption during T_2. It should be noted that practically no substrate was available during T_2, because available substrate had been washed away by tap water. The mass of oxygen not accounted for by HOC is denoted as "unknown", which was 36-62% of COD removal. Oxygen balance of R_2 was similar with R_1 and hence omitted here.

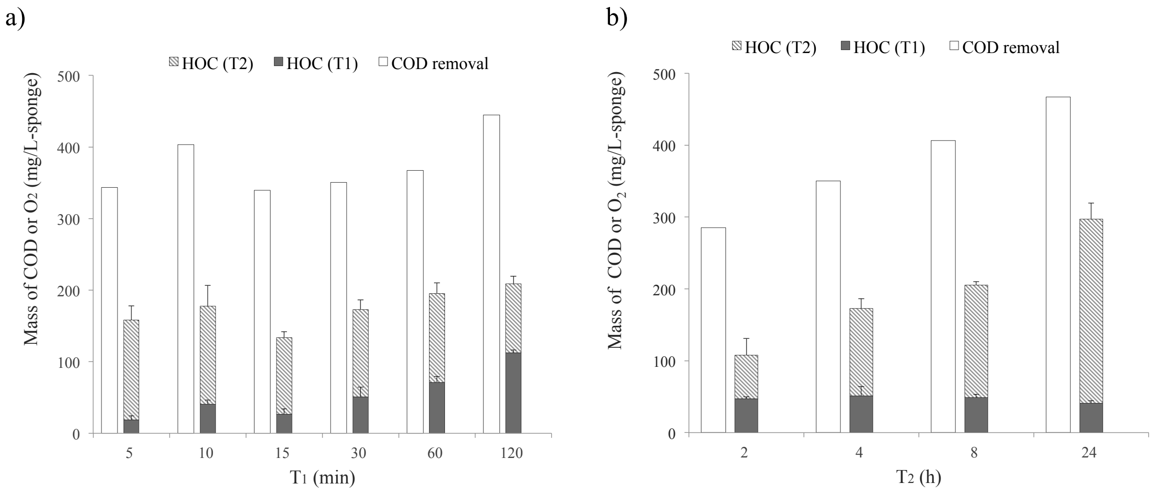


Fig 16 Oxygen balance of R_1, a): Experiment 1, T_1 varied while T_2 = 4 h, b): Experiment 2, T_2 varied while T_1 = 30 min, error bar: standard deviation of HOC in T_1 and T_2, N = 5.

In Experiment 3, COD removal of R_1 was higher than that in Experiment 1 (**Fig 17** a). HOC in T_1 was 2-15% of COD removal, and HOC in T_2 was around 30% of COD removal, indicating suppressed oxygen consumption under low temperature. Share of unknown part was more than 50%. Oxygen balance of R_2 was similar, although the data for the final point was not successfully taken due to problem of TOC analyzer (**Fig 17** b).

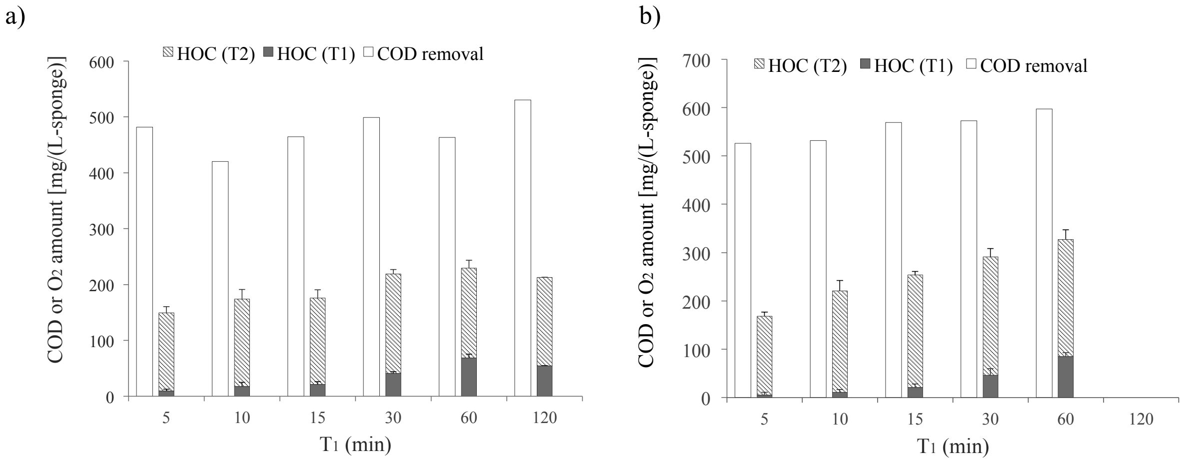


Fig 17 Oxygen balance of a) R_1, b) R_2, T_2 = 4h, ambient temperature: around 15°C

3.2.4 Variation of PHA

PHA is a typical form of storage compounds inside microorganisms, when volatile fatty acids (VFAs) including acetate are available as carbon source. Variation of PHA content per volume sponge within a cycle is illustrated in **Fig 18**. The magnitude of PHA was comparable to HOC. For R_1, PHA increased by 30% of the lowest value within 5 min and reached the peak at 10 min. Then, PHA content remained at a steady state. Entering famine duration, PHA started to decrease and was lowest at the end of the cycle. These observations imply that PHA can be quickly produced in a short period. On the other hand, PHA content of microorganisms in R_2 did not change obviously throughout the cycle. The results of other two batches of experiment did not follow the trend of **Fig 18**. More specifically, PHA content increased during the whole cycle, or substantially fluctuated so that no trend could be noticed (see Appendix).

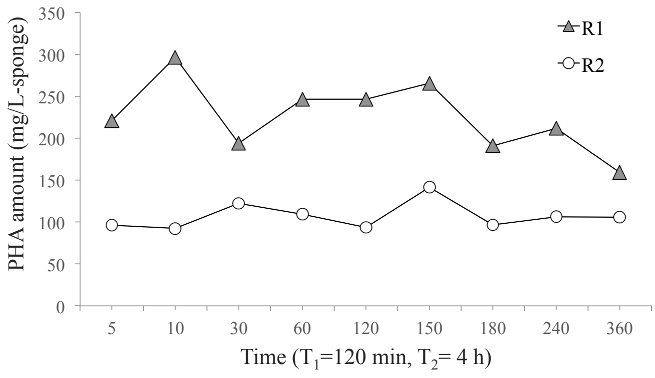


Fig 18 Variation of PHA within a cycle (T_1 = 120 min, T_2 = 4 h)

3.3 Discussions

3.3.1 Mechanisms of organic matter removal

Organic matter removal initiated from the physical absorbance of sewage by sponge. As sewage flow is fast, we assume only physically absorbed part of sewage is accessible to microorganisms. After physical absorbance, biological utilization of absorbed organic matter in sewage took place.

I presume one mechanism of biological organic matter removal to be microbial storage. Microbial storage is a process that microorganisms transform substrate into intracellular polymers as a source of energy, carbon, or reducing power to survive growth-limiting conditions (92). Under feast-famine condition, microbial storage proceeds along with microbial growth in feast duration, and storage compounds are consumed for microbial growth and maintenance in famine duration (93, 94). Storage usually dominates over growth (95, 96). Feast-famine condition is favorable for floc-forming cultures, which exhibit rapid settling rates, low net growth and high resistance to extended starvation periods (97-99). Inside such microorganisms, storage compounds are granules that distributes non-randomly in the cell lumen (100, 101). Serafim et al. explained mechanism of PHA storage by lack of sufficient enzymes or RNA required for microbial growth (101).

Significance of microbial storage in biological organic matter removal is supported by multiple evidences. The first one is HOC in T_2. During T_2 no substrate is available, thus the observed HOC should be consumed for oxidizing storage compounds. HOC in T_2 was up to 65% of COD removal, which confirms the importance of microbial storage quantitatively. The yield of storage compounds is comparable with findings from other studies, with acetate being a major substrate (101-106).

Another evidence is the peak of HOCR in Phase 1 of HOCR pattern. High HOCR is related with microbial storage in both activated sludge and attached growth systems under feast-famine condition (99, 103, 106-108), as a reflection of high substrate intake rate accompanied by active respiration (97, 109). A fast storage response ensures the amount of storage compounds and hence the competitiveness of microorganisms with such capability (98).

Phase 3 in HOCR pattern also supports my hypothesis, because microbial activities proceed more slowly on stored matter than on substrate (97, 98, 103, 108, 110). This also coincides with the low organic matter removal efficiency with short famine duration. Decreasing trend of HOCR in Phase 3 functions as additional evidence for microbial storage, for consumption rate of storage compounds is correlated with their amount (96,

103) . Phase 1 and Phase 3 depict microbial storage from kinetic perspective, that microbial storage proceeds rapidly in feast duration and storage compounds are degraded gradually in famine duration.

Other possible explanations for biological organic matter removal exist as well, considering HOC in T_1 and the unknown part in oxygen balance. HOC in T_1 is credited to microbial growth and maintenance, supported by Phase 2 in HOCR pattern. Moreover, HOC in T_1 can be triggered by microorganisms without storage capacity, considering in attached system the microbial community is diversified. Unknown part can be attributed to activities of sulfate-reducing bacteria, microbial growth, and storage compounds that were not depleted.

In summary, mechanisms for organic matter removal of ICOP extend to both physical absorbance and biological utilization. An essential mechanism for biological organic matter removal under feast-famine condition is microbial storage. Microbial storage provides an explanation for the observed steady organic matter removal efficiency, removal within short feast duration, and system robustness against long famine duration.

3.3.2 Carbon flow model and influencing factors

Following the discussion on mechanism, we put forward a qualitative model to describe carbon flow in an ICOP reactor under feast-famine condition (**Fig 19**). With sewage flow, free carbon in sewage is physically absorbed in sponge, marking the initiation of feast duration. In feast duration, physically absorbed carbon is transformed into storage compounds, new biomass, or oxidized into CO_2. Then, the rest of absorbed carbon is washed away by tap water and the reactor enters famine duration. In famine duration, storage compounds are transformed into biomass, oxidized into CO_2 or carried over to next cycle. Finally, the cycle starts over if there is additional carbon supply, otherwise microorganisms decays after the depletion of storage compounds.

According to this model, influencing factors of organic matter removal efficiency include sewage to sponge volume ratio and length of famine duration. For physical absorbance, lower ratio of sewage volume to sponge volume results in higher share of physically absorbed carbon, supporting more efficient purification. For the consequent biological removal, longer famine duration is recommended. During longer famine duration, more storage compounds will be consumed, and consequently more carbon will be captured and stored by microorganisms in the next cycle. Considering that microbial storage takes place rapidly and organic matter removal efficiency is not sensitive to length of feast duration, I assume controlling feast duration is less critical.

Temperature and running time are two other influencing factors of organic matter removal, which can not be clearly separated in this study. I speculate low temperature suppressed microbial activities including growth, maintenance and storage. This is supported by less HOC in T_1, lower HOCR in Phase 1 and less share of HOC of COD removal. This opinion shares similarity with the result of Johnson et al., that yields of storage compounds increase with temperature (111). Meanwhile, other studies raise a different opinion, that with higher temperature substrate is distributed more to maintenance and less to storage compounds and biomass (94, 95, 112).

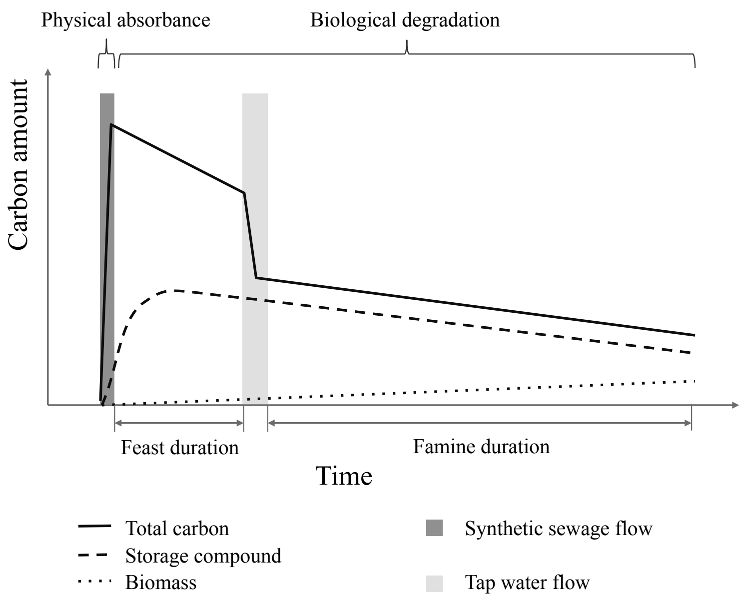


Fig 19 Model proposal for carbon flow in an ICOP reactor under feast-famine condition

However, other results from Experiment 3 are in contrast with this hypothesis, including higher TOC removal efficiency, larger HOC in T_2 and higher HOCR in Phase 3. One possible explanation is that influence of running time outweighed the influence of temperature. With longer running time, microbial community in reactor may have gained higher density and more diversity. In addition, even filter flies developed in this system, indicating a longer food chain. McSwine et al. reported that different communities of microorganisms demonstrate different maximum oxygen utilization rate (OUR) under feast-famine condition (113). Further, filter flies do not trigger variation in HOCR towards the feast-famine condition. Hence, overall response of the system towards feast-famine condition should be more complicated and the characteristics of PHA-accumulating microorganisms are less pronounced with longer operation time.

Overall, at low temperature the storage response of microorganisms is prohibited, but running time and development of filter flies exhibit larger influence than temperature. Consequently, we propose in the range of 15-25 °C, influence from temperature on system performance is slight.

3.3.3 Organic matter load and removal rate

Organic matter removal rate is reflected as daily COD removal per volume sponge [gCOD /(L-sponge · d)]. Organic matter removal rate increased linearly with organic matter load in the tested range (Fig.8). To assess the average organic matter removal rate, we chose a rather middle load in the tested range, that is, 4 gCOD /(L-sponge · d). Under such load, 2 gCOD/(L-sponge · d) could be removed. The estimated organic matter removal rate is within the same range but lower than the result of Sotelo et al. (53), that 1.3-9.2 gCOD/(L-sponge · d) was removed by ICOP receiving lipids. There are two possible explanations for this difference. First, organic matter load in their study was much higher than mine, which might result in higher removal rate. Second, substrate in their study was in contact with sponge for the whole cycle (8 h), whereas in my study the contact time was much shorter. In addition, my assumed load is consistent with load from a single household, hypothesizing sponge volume in sewer is around 30 L per capita. Overall, I propose 2 gCOD/(L-sponge · d) to estimate performance of ICOP for application at sewer upstream.

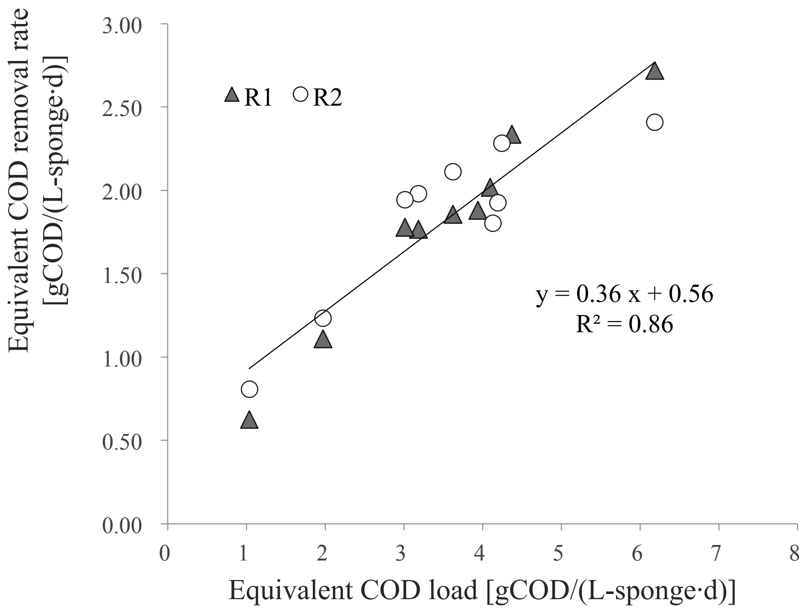


Fig 20 Organic matter load and removal rate, an integrated result of Experiment 1 and Experiment 2 (COD removal estimated from TOC removal)

3.3.4 Estimation of performance at sewer upstream

With the average removal rate, a projection is made to identify the potential of applying ICOP at sewer upstream. It is assumed here that in upstream sewer pipe (250 mm diameter), 1 cm thick sponge is installed occupying 1/3 of pipe surface area. If length of upstream sewer per capita is 10-15 m (a rational estimation for cities), volume of sponge inside will be 26-39 L per capita. Correspondingly, organic matter removal rate will be 52-78 gCOD/(cap · d). Given the load of domestic sewage as 100 gCOD/(cap · d), organic matter removal efficiency should be 52-78%. In real world, the removal efficiency is also influenced by temperature, sewage composition, available pipe length per capita, etc. Still, this projection suggests the promising application of ICOP at sewer upstream.

3.3.5 PHA generation and reflections on experimental methods

PHA variation of R_1 provides evidence for microbial storage from both quantitative and kinetic perspectives, though he observation was not so reproducible. Meanwhile, the different PHA variation pattern for R_2 favors the discussion in section 3.3.1, that mechanisms other than microbial storage may gain importance with longer running time and as higher level organism develop in R_2.

The measurement results of PHA were not as expected for other batches, which lead to a reflection on the experimental methods. First, the way of sampling and calculating may affect the result, considering the heterogeneous nature of attached growth system. In the ICOP reactor, different microbial communities were spotted from upper part to lower part of the sponge. Although samples were taken from different part of the sponge, whether an averaged result can be a representative of the whole system remains a question. In addition, amount of biomass attached on the sponge was not the same, but PHA content here was computed as the amount of PHA per volume sponge. For future studies, PHA content can be evaluated based on biomass amount rather than sponge volume.

The influence of predators is another question, in that predators may not have the ability to store carbon, and they are not known to store carbon in the form of PHA. Amount of predators was substantial during the experiment, and they may have contributed to inconsistent PHA variation pattern. For future studies, separating predators in advance may be worthwhile to be considered.

Separation of extracted solution from sponge media was carried out by physical extrusion, which may not be enough to overcome surface tension of the sponge. Here, a possible improvement is to wash the sponge with water for few times, mix the wash liquid with the reaction mixture, then neutralize the sample and fix its volume.

Proper time resolution for sampling is also a topic to discuss. Time between sampling should be large enough to buffer the time for sampling. This is because taking sample requires cutting sponge from different places, submerging sponge into digestion solution, and fully mixing sponge with digestion solution manually. In my experience, a period longer than 10 min is recommended.

3.4 Chapter Summary

In this chapter, the performance of lab-scale ICOP reactor under simulated sewer upstream condition was explored. Results and discussions from this experiment are summarized as below:

1) ICOP exhibited stable organic matter removal efficiency under dynamic feast-famine condition, even for short feast duration and long famine duration. Yet, short famine duration was not favorable.

2) The HOCR pattern in a cycle could be divided into 3 phases, and COD removal in one cycle outweighed the sum of HOC.

3) Both physical absorbance and biological degradation contribute to organic matter removal. Up to 65% biological organic matter removal could be attributed to microbial storage, which proceeded rapidly in feast duration and degraded gradually in famine duration.

4) A qualitative model of carbon flow was proposed, with sewage to sponge volume ratio and famine duration being influencing factors.

5) Low temperature prohibits microbial storage, whereas it influence can be covered by running time.

6) On average, organic matter removal rate was 2 gCOD /(L-sponge · d). Estimation with average removal rate favors the utilization of ICOP at sewer upstream.

CHAPTER 4 IN-SEWER PURIFICATION AND ENVIRONMENTAL SUSTAINABILITY IN WASTEWATER MANAGEMENT

With understanding in the performance of ICOP at sewer upstream condition, this chapter seeks implications for applying ICOP as well as in-sewer purification in wastewater management system. A system with greater environmental sustainability by incorporating in-sewer purification will be the focus of this discussion. Arrangement of this chapter is as below. The story started from an overview of the sustainability-related issues, deficiencies of traditional centralized system, and possible solutions (Section 4.1). Following that, the narrative tried to quantify the reduction of energy consumption by ICOP through scenario analysis (Section 4.2). To elaborate this discussion, a closed water loop system by combining in-sewer purification and water reuse was proposed, and potential benefits and its optimum scale were discussed (Section 4.3). And then, the story was wrapped up with a general discussion of extending the proposed system (Section 4.4), as well as considerations for its application in practice (Section 4.5).

4.1 Overview

The sustainable exploitation of resources and energy becomes an issue when human is growing exponentially in the finite earth system. From industrial revolution up until now, global population increased by 3 billion, which is one third of entire number of human in history. The growing trend continues, so that 10 billion people are expected on earth by 2100 (12). Vast population base and rising living standard result in greater consumption of resources and energy, sometimes in a non-reversible form. Take the water sector as an example, an increase in water use and pollution of water is noticed for the past century, with accelerating rate of change (114). Although water supply rate from global hydrological cycle still exceeds rate of consumption, many local situations suffer from water stress due to uneven distribution of water resources. Water stressed areas rely heavily on agricultural and industrial products imported from water-rich areas, which is termed as a transport of virtual water (115). Such practice temporarily elevates water stress, at the expense of greater energy consumption and higher vulnerability towards drought. To solve such problem, the net benefit for a resource-energy nexus should be pursued. As a basic part of resource and energy flow in modern infrastructure system, wastewater management should incorporate environmental sustainability as a new performance indicator.

With growing motivation for environmental sustainability, the centralized system is receiving criticism for large environmental footprint, and its failure in conserving resources (116), in spite of its success in removing pollutants . To list a few, centralized water/wastewater system relies heavily on water as a transportation media, resulting in a decrease of water flow from upstream to downstream of surface waterbody, or descending local groundwater table (7, 62, 117-119). Centralized system consumes energy intensively for long distance transportation of sewage and aeration for sewage treatment, as well as chemical for disinfection (7, 62, 119, 120). Moreover, nutrients in sewage can not be effectively recycled with centralized system, while additional nutrients generates eutrophication in receiving water body (7, 9, 62, 117-119). Further, many systems in U.S. and Europe are still relying on combined sewer, and combined sewer overflow (CSO) leads to pollution during heavy rainfall (117, 118, 120). In addition, micropollutants, heavy metal, and pharmaceutics remain in treated sewage and sludge (7).

To address the sustainability challenges confronting centralized system, solutions extend to two aspects: incorporating technologies with higher efficiency into current system, or revising the overall paradigm of wastewater management (9, 62, 121, 122). In-sewer purification is one example for high-efficiency technology, by reducing energy consumption for sewage treatment. Some other technologies that favor environmental sustainability will be introduced in Section 4.4. Two ideas are proposed for the new paradigm of wastewater management in this study: decentralized wastewater management, and a closed water loop.

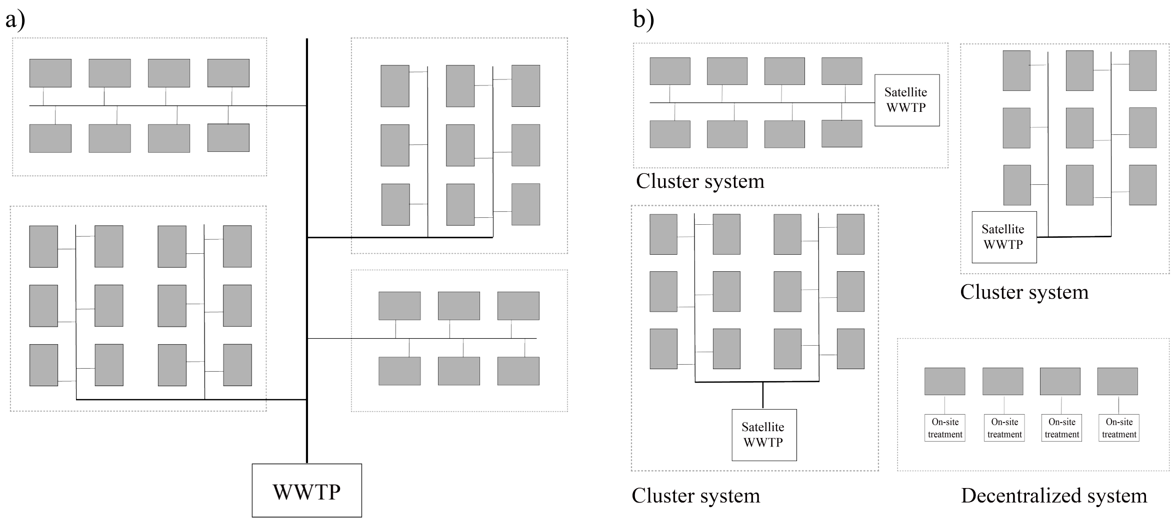


Fig 21 A schematic of a) centralized wastewater management system, b) decentralized and cluster wastewater management system

Decentralized wastewater management refers to the system where sewage is collected with minimal-scale sewer to a small treatment system, treated and discharged near to the source. There is actually not a clear defined threshold between centralized and decentralized system (118). To make the discussion clearer, in this study the boundary for decentralization encompasses on-site treatment system for single or several households. And I define here cluster system to situate between on-site system and centralization (**Fig 21**). Cases for decentralized system contain the septic tank and drainfield system (123), Johkasou system in Japan (54), and multiple forms of on-site systems in U.S, Australia, and Italy (123).

The concept of closed water loop is defined here as a water management system with minimal net water extraction from natural environment, by maximal reuse of water to support water demand. The extent of loop, therefore, can be evaluated by the share of net water extraction to entire water use. Inspiration of this definition derives from work of Tambo, where a water system serving for 10 billion people on earth is envisioned, and reducing net water exploitation is a key solution (12).

4.2 Energy Consumption Reduced by In-sewer Purification

In-sewer purification is most appealing in its reducing energy cost for treating sewage. The reduction in energy consumption for sewage treatment will be evaluated by scenario analysis, considering a centralized system with ICOP applied at sewer upstream.

4.2.1 Scenario settings and parameters

Three scenarios are considered for a virtual community, corresponding to low, medium, and high population density (**Fig 22**). The original map shown in **Fig 22** a) was taken from a part of Kashiwa City with buildings and sewers around 2015. Area of the given community was 40.4 ha, and population density was 8673 cap/km^2. I took this community to simulate the size and scale of actual communities. For the scenario analysis, the location, population density and sewer network were manipulated. To generate scenario with lower population density, buildings were manually removed and sewers were accordingly adjusted from **Fig 22** a). In **Fig 22** b), population density was around one fourth of original value, and in **Fig 22** c), population density was half of the value in **Fig 22** b).

Fig 22 Sewer network layout for different scenarios, a) high population density, b) medium population density, c) low population density

The whole community is served with sewer network, with which sewage is transported to a large WWTP outside the community. Definitions for house sewer and lateral sewer are the same as described in Chapter 2. For main sewer, here it referred to an aggregation of sub-main and main sewer for convenience. Local geography is assumed to be flat plain, and climate is rendered as subtropical with seasonal monsoon, so that performance of ICOP can be estimated with average performance in Chapter 3 [2 gCOD /(L-sponge · d)]. The rate was assumed to be the same for all house and lateral sewer pipes.

Characteristics about sewage emission are adopted from Chapter 2. Quantity of sewage is 200 L/(cap · d), and the COD load is 110 g/(cap · d). For sewer pipe with ICOP, diameter of upstream sewer pipe is assumed to be 250 mm, with sponge occupying one third of pipe inner surface. Thickness of sponge is 1 cm, and consequently volume of sponge is 2.6 L/m-pipe. At the final WWTP, conventional activated sludge method is applied, energy consumption of which is estimated as 1 kWh/kgCOD (124). Energy consumption on pollutant load basis is higher for smaller scale WWTP (124), but here the influence from given community on overall flow rate of receiving WWTP is omitted. Additional energy use for nutrient removal at WWTP is not taken into account in this study.

4.2.3 Results and discussion

For three scenarios, expected COD removal by ICOP and net energy consumption for sewage treatment are exhibited in **Table 5**. The COD removal in sewer increased with descending population density, which can be explained by longer pipe length per capita. Similarly, energy consumption on capita basis decreased with smaller population density. Given energy consumption as 0.11 kWh/(cap · d) for a system without ICOP, the reduction in energy consumption was 57% for medium population density and 79% for low population density. Such estimation proves the potential for ICOP to improve energy neutrality of wastewater management system. And the application of in-sewer purification is proposed to areas with low to medium population density, in order to maximize its potential.

Table 5 COD removal and energy consumption for different scenarios

Indicators	Units	Scenario A	Scenario B	Scenario C
Population density	cap/km2	8673	1982	991
Population	cap	3500	800	400
Length of sewer		34565	23168	16070
Main sewer	m	5151	3944	2660
Sewer upstream	m	14707	9612	6705
Lateral sewer	m	9212	4758	3078
House sewer	m	5495	4854	3627
COD load	kg/d	385	88	44
COD reduction in sewer	kg/d	76	50	35
Energy cosumption at WWTP	kWh/(cap.d)	**0.088**	**0.048**	**0.023**
Percentage of energy saving	%	**20**	**57**	**79**

4.3 New Wastewater Management Paradigm with In-sewer Purification

4.3.1 System proposal: closed water loop at cluster scale

A cluster system is suggested for application of in-sewer purification. In more detail, in-sewer purification is combined with satellite WWTP, which is meant here for small scale WWTP located within the boundary of community. Several reasons account for this proposal. One is that in-sewer purification favors small to medium population density, and hence sewage flow rate is too small for large WWTP. The pollutant load for WWTP is also alleviated, so that treatment at satellite WWTP is sufficient. Furthermore, confining the wastewater system within local boundary limits the cost for long distance sewage transportation.

On the basis of cluster system, a closed water loop can be established in integration with water reuse. The concept of closed water loop system and traditional centralized system is demonstrated in **Fig 23**. A centralized system extracts all the water it needs from natural environment by long distance transportation, and then disposes treated sewage downstream far from its origin. Whereas in a closed water loop system, treated sewage is circulated so that extraction of natural water is reduced. Water extraction and treated sewage disposal occurs all within local boundary, with less influence on the natural hydrological cycle. Application of a closed water loop system is proposed for peri-urban area, and small town center.

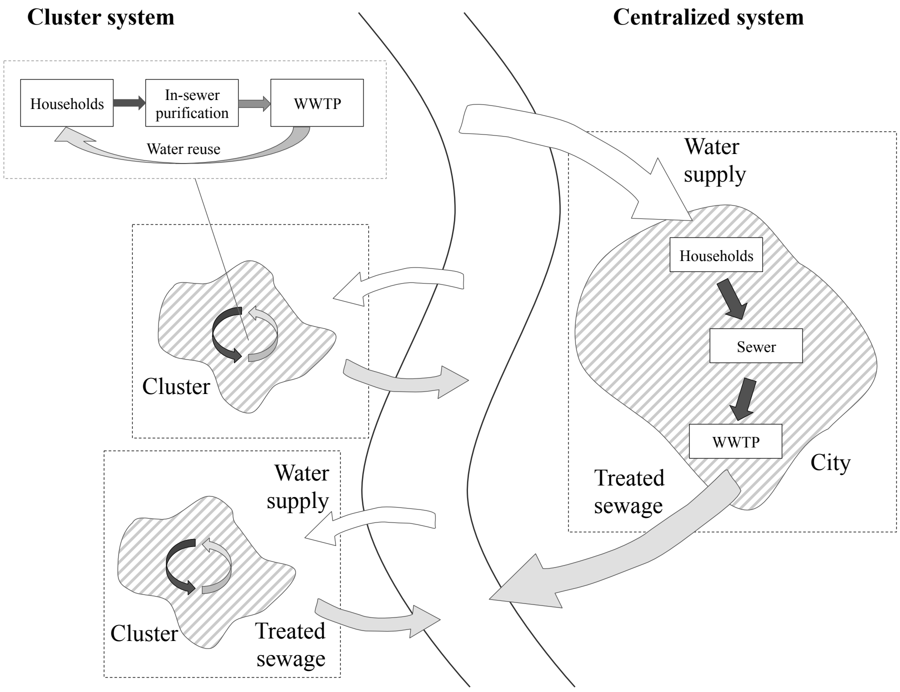


Fig 23 A closed water loop system and a traditional centralized system

Water reuse is the essential part of closed water loop system. Potential for water reuse is generally divided into potable reuse and non-potable reuse (NPR). Potable water reuse includes direct potable reuse (DPR) that is only in practice in Windhoek, Namibia, and indirect potable reuse (IPR) by recharging groundwater or surface water with treated sewage (125-127). Non-potable reuse is commonly and internationally applied, mostly in decentralized system (11, 126-128). Options for NPR contain agricultural irrigation, industrial reuse (cooling water, boiler makeup water, process water), urban reuse (car washing, toilet flushing, fire protection), landscape irrigation (natural restoration), and environmental and recreational use (parks, green belts, golf courses) (128-131).

Quality requirements for reclaimed water differ with its usage, which requires different treatment process (132). Regarding NPR in cluster system, the combination of in-sewer purification and treatment with attached growth system at satellite WWTP is proposed, for its low energy consumption and sludge generation compared to activated sludge system. A final disinfection procedure is needed to control pathogen level. Another option is the in-sewer purification and membrane separation system. The membrane technology is gaining popularity for its high efficiency in producing high-quality treated water, however, membrane fouling is a major obstacle in practice. Pretreatment of sewage by in-sewer purification should reduce potential of membrane fouling and improve overall performance of the system.

4.3.2 Expected benefits

The proposed closed water loop system presents greater environmental sustainability, with a net decrease in energy consumption and water extraction. Reduction in energy consumption is achieved by in-sewer purification, and the energy saved offers more opportunities for water reuse (130). Greater water reuse, consequently, reduces the demand for fresh water, as well as energy cost for transporting and treating water. In such manner, a positive water-energy nexus can be achieved with closed water loop system.

Another environmental benefit of this system is that it conforms more with natural hydrological cycle. In this cycle, extraction of local water resource is reduced by water reuse, and treated sewage is returned to local water body with satellite WWTPs. Maintaining a natural hydrological cycle is advantageous in conserving local water resource and the local ecosystem. The proposed system also demonstrates more resilience towards water stress, because reclaimed water functions as a stable and additional water source. The study of D'Odorico et al. supports this idea, that a community relying on virtual water import (agricultural products) exhibits higher mortality rate during drought events (133).

4.3.3 Optimum spatial scale

The optimum spatial scale of a cluster system requires careful evaluation, considering the cost for constructing pipeline and pumping against building a new satellite WWTP (134). The introduction of closed water loop makes this problem more complex, by introducing environmental benefits as well as additional capital and energy cost for water reuse infrastructure. Hereby, a framework is needed to determine proper spatial scale of a closed water loop system.

A framework proposal is illustrated in **Fig 24**, with its interest in economic and environmental perspectives. To start with, the local geometric conditions should be assessed to determine sewer network layout, and need for elevation. With this information, the cost for sewer pipe, WWTP and pump can be calculated. Meanwhile, energy consumption for collecting and treating sewage, and transporting reclaimed water can be estimated, together with energy saving by in-sewer purification, and amount of reclaimed water. A final decision on the merit and demerit of the system depends on local needs, and multi-criteria analysis is one tool for such objective.

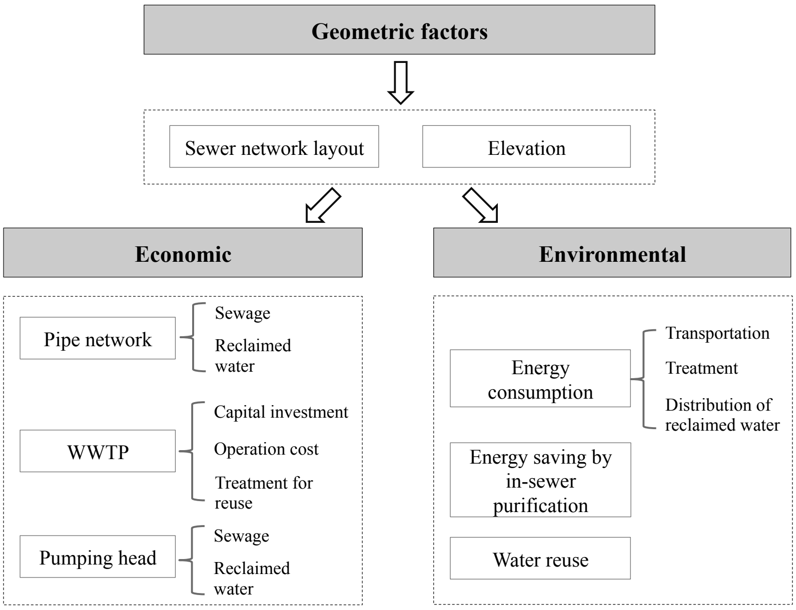


Fig 24 Proposed framework to evaluate optimum spatial scale for a closed water loop system

To list a few existing studies, Newman et al. proposed community scale (50-500 households) for its opportunity to form a closed-loop, in terms of social, economic and environmental rationale (121). Lee et al. stated community scale is desired when isolated from existing WWTP, while integration with existing centralized system is better when community is close to a centralized WWTP (135). Similarly, Kavvada et al. suggested the scenario with least energy consumption and greenhouse gas emission is a cluster system at high-elevated area, whereas the worst case is a small cluster system near an existing large WWTP (136). Based on the information above, this study proposes catchment or smaller scale to be feasible for a closed water loop system.

4.4 Further Extension from New Paradigm

The closed water loop system can be expanded to maximize environmental sustainability, as demonstrated in **Fig 25**. One way is to deepen the extent of water loop, by reducing water consumption, and harvesting rainwater as additional water supply. Water consumption can be cut by water saving appliances at household level, examples of which are low-flow toilets, showerheads, and washing machines (116). Water consumption for a cluster is also cut by increasing water use efficiency in agricultural irrigation and industry processing. Rainwater harvesting technology collects rainwater from rooftops for household use, such as toilet flushing, laundry, and garden irrigation (116, 130).

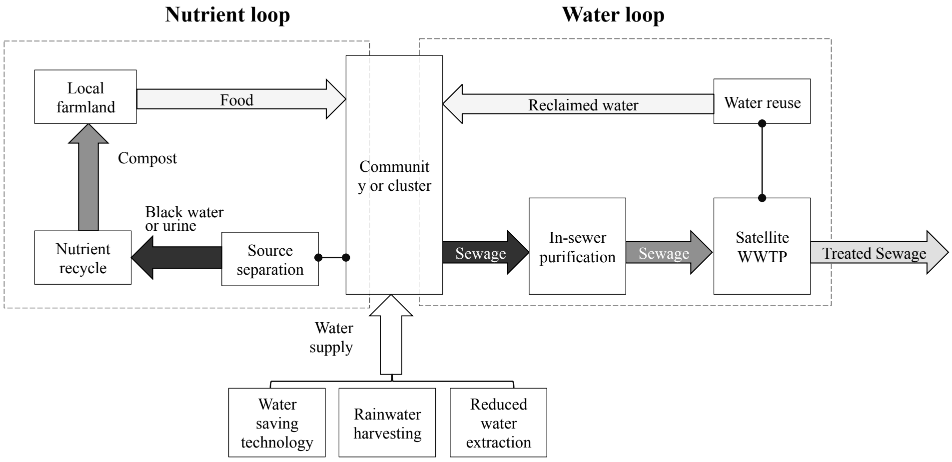


Fig 25 Extension of a closed water loop system

Another approach is to simultaneously close the loop for nutrient by recycling nutrient from sewage. Nutrients in domestic sewage stem primarily from food intake, and therefore they are strongly suggested to end in agricultural land rather than the water body (137). Technologies for nutrient recycle include: biosolid production through anaerobic digestion, composting and heat drying, controlled struvite crystallization, calcium phosphate precipitation, and recovery through aquatic products (54, 131).

Source separation is recommended to be in combination with nutrient recycle, especially at household scale (11, 132). Source separation indicates separate collection of sewage streams with different qualities (138), typical practices of which are dry toilet (separation of black water) and urine-separating toilet (separation of urine) (54).

4.5 Suggestion for Application and Limitations at Current Stage

Imagining a picture for future application of in-sewer purification and ICOP is of value, still, their development is at an infant stage and the road forward can be long and bumpy. A comprehensive and holistic view is needed to stay clear and objective. In this section, some practical factors to be weighed when utilizing in-sewer purification, together with limiting factors at current stage are shortly discussed.

4.5.1 Suggestion for application

As indicated in the previous sections, in-sewer purification is proposed for cluster system in combination with satellite WWTP. The desired population density is from medium to low, and the cluster system should be implemented for peri-urban area, suburb, and small town center.

Some other general demand should be satisfied when applying in-sewer purification. Separate sewer rather than combined sewer should be the target of in-sewer purification. The given area shall not be too hilly or rocky for implementation of sewer system. Certain level of capital investment and technology is also needed to introduce sewer system. Feasibility for launching in-sewer purification is greater for new development, or areas with a need to replace old infrastructure. Local climate should be favorable for biological processes, and sub-tropical and tropical areas are suggested.

4.5.2 Limitations at current stage

Despite the potential of in-sewer purification in enhancing environmental sustainability, limitations exist in other perspectives than environment. The concept of sustainability in wastewater management system covers the triple bottom line: economy, society and environment (9, 123, 139, 140), as well as a technical viewpoint (6, 139, 141). Under this framework, limitations for launching in-sewer purification in practice expand to economic, social, and technological aspects.

The economic perspective remains a major challenge, especially for developing countries (123). Although capital investment for WWTP can be saved by introducing in-sewer purification, the technology itself brings about extra expenditure. As indicated previously, considering water reuse into the system perplexes the situation. In order to understand the collective economic outcome of applying in-sewer purification and water reuse, a valid cost-benefit analysis that quantify and monetize environmental benefits is essential (119).

Despite the progresses in ICOP as enhanced in-sewer purification, many technology-related issues are yet to be solved. Behavior of solids with ICOP is one topic, considering that in domestic sewage solids makes a considerable share in organic matter. Sources of solids in domestic sewage include food residues, feces, toilet paper, hair, body fats, etc. (63). Solids removal efficiency of ICOP is closely related with clogging of sewer and quality of treated sewage. In relation with solids, sludge management in a system with in-sewer purification should be another topic.

Apart from solids, influence from geography on performance of ICOP should be more clearly understood. Local geography influences slope of sewer pipe, and subsequently water level in sponge. With larger slope sewage is drained more rapidly, and microorganisms get greater chance to access oxygen in air to oxidize captured organic matter in sewage. On the other hand, if the slope is too small, sponge may be submerged in sewage all the time, which prohibits aerobic process (142).

Furthermore, life span of sewer with ICOP is also to be investigated to determine temporal scale of the related system. Tambo proposed a global-scale transition into new paradigm would be a task for the entire 21st century (12). Life span of a common sewer is 50-70 years, however, life span of sewer with ICOP is dependent on the sponge media. Sponge media inside sewer is subject to hydrological sheer stress, biological and chemical corrosion, and activities of protozoa, insects and small animals in sewer. Under such conditions, the duration of sponge should be decided with data from practical experience. Approaches to replace damaged sponge in sewer are also required.

Social factors will be equally or even more decisive for application of in-sewer purification in real world. Public perception and acceptance matter considerably when community makes a choice among technologies, sometimes even outweighing their actual performance. As a result, deepening public understanding in sewage management by education is necessary to guide a rational decision. Favorable policies and institutional framework supports introduction of new technology. Public health consideration is especially denounced for water reuse and nutrient recycle (143), considering emerging micro pollutants, heavy metals and pharmaceutics in domestic sewage (7). Hence, standardized regulations for water reuse are desired, to achieve which goal institutional support and reform are suggested as well (143). Accumulation of niche scale experience is still lacking, which allows an empirical foundation and trigger fundamental changes in social-technology regime (119).

4.6 Chapter Summary

This chapter discussed contribution of ICOP and in-sewer purification to environmental sustainability, in a centralized system and a closed water loop system. Key conclusions drawn from this chapter are listed as below:

1) Issues related with environmental sustainability are confronting centralized wastewater management system. These issues can be solved by introducing more efficient technology into current system, or altering the overall paradigm of the system.

2) In-sewer purification is favorable for environmental sustainability by reducing the energy cost for sewage treatment. In-sewer purification is most efficient for areas with low to medium population density.

3) In-sewer purification is proposed for application at cluster scale with satellite WWTP. A closed water loop can be formed by adding water reuse into the system. These generate a net diminution in energy consumption of wastewater management system and improve total water cycle.

4) The extent of water self-efficiency can be further enhanced by incorporating water saving technology and rainwater harvesting. And a closed nutrient loop is available with source separation and nutrient recycle technologies.

5) Some general requirements should be met to apply in-sewer purification. At current stage, limitations for launching in-sewer purification expand to economic, technological, and social aspects.

CHAPTER 5 CONCLUSIONS

5.1 Key Findings

The general aim of this study was to explore the potential of applying ICOP at sewer upstream for enhanced in-sewer purification, and greater environmental sustainability in wastewater management system. This aim constituted of three specific objectives, findings of which are provided below.

The first objective was to gain an understanding in in-sewer purification and sewer upstream for its application. In-sewer purification refers to the concept of actively utilizing sewer processes for sewage treatment. Natural in-sewer purification can be enhanced, and one approach is to apply ICOP in sewer, by installing sponge media to retain microorganisms with intermittent sewage flow. Application of in-sewer purification was advised for sewer upstream, being a major component of sewer network. At sewer upstream, sewage derives directly from usage of household appliances, and consequently sewage quantity and quality are highly scattered. And at sewer upstream, sewage flow pattern is characterized by varied intermittency, prevailing dry condition, hydraulic instability, and large peak factor.

The second objective was to explore performance of ICOP under sewer upstream conditions. Upstream sewage flow creates a feast-famine condition for microorganisms in sewer. Under dynamic feast-famine condition, ICOP exhibited stable organic matter removal efficiency, even for short feast duration and long famine duration. Yet, short famine duration was not favorable. Mechanisms of organic matter removal contained both physical absorbance and biological utilization. For biological removal, role of microbial storage was essential, which proceeded rapidly in feast duration and degraded gradually in famine duration. Influencing factors of organic matter removal extend to sewage to sponge volume ratio, famine duration, temperature, and system running time. The average organic matter removal rate was 2 gCOD /(L-sponge · d), based on which performance of ICOP in application can be evaluated.

The third objective was to explore role of in-sewer purification in elevating environmental sustainability in a wastewater management system. In-sewer purification can be introduced into centralized system, for the purpose of conserving energy for sewage treatment. In-sewer purification was estimated to be more efficient for areas with low to medium population density. Then, a cluster system can be formed with in-sewer purification and satellite WWTP. By adding water reuse into the system, a net decrease in energy and water consumption is achievable. For practical application of in-sewer purification, some general requirements should be met, and obstacles are spotted in economic, technological, and social aspects.

5.2 Limitations and suggestions

Limitations of this study are sum up as follows.

For the literature review, although a timeline for the development of in-sewer purification and related branches was provided, this study did not go further into the quantitative results of each study. A cross-comparison among studies was not covered, either. The review of sewage quantity, quality and flow pattern at sewer upstream could also be extended on regional basis.

For the experiment part, reliability of PHA measurement needs to be questioned due to limitations in current methodology. Moreover, we targeted only at removal of soluble organic matter, whereas particulate organic matter in real sewage can not be neglected, e.g. food wastes, feces and toilet paper.

For the final discussion, social and economic perspectives of in-sewer purification were only touched shallowly, however, understanding of these factors is essential for future application.

Corresponding to the limitations, some suggestions are proposed for future study on ICOP and in-sewer purification, including

1) a wider and deeper review of in-sewer purification on current basis, from its mechanism, timeline of development, to quantitative results from experimental studies, and model development for evaluating in-sewer purification.

2) the behavior both biodegradable and non-biodegradable solids in ICOP under sewer upstream condition.

3) the dynamics of microbial community of ICOP, which is subject to sewer upstream condition for long-term.

4) a pilot-scale study where ICOP is introduced to household or community, with analysis from social, economic, as well as environmental aspects.

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APPENDIX

The entire data for PHA analysis are displayed here for reader's reference.

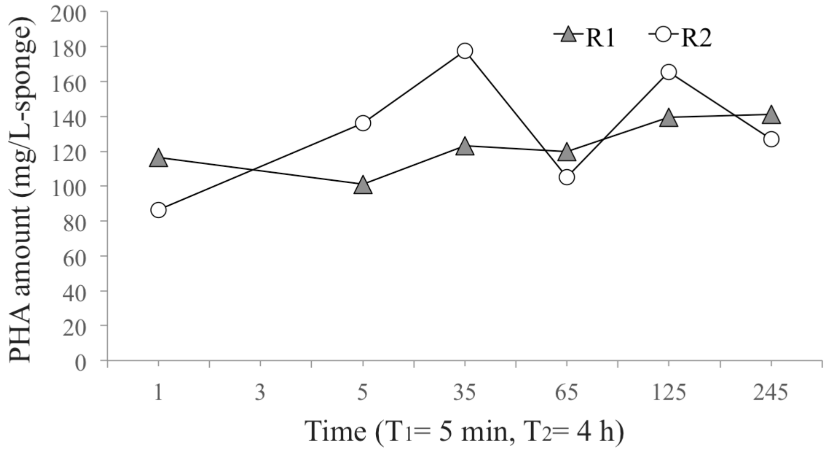

Fig 1 Variation of PHA within a cycle (T_1 = 5 min, T_2 = 4 h)

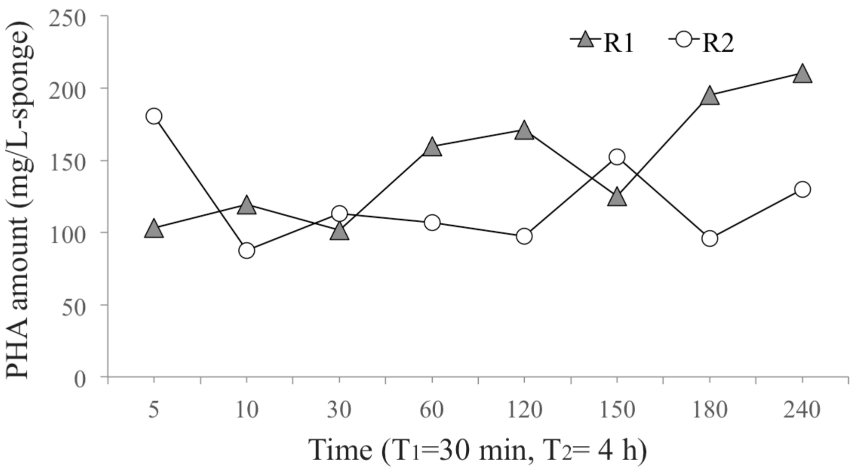

Fig 2 Variation of PHA within a cycle (T_1 = 5 min, T_2 = 4 h)