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Doctoral Thesis in Civil and Environmental Engineering

Study on the Resource Circulated Sanitation (RCS) Using Nitrifying Microorganisms

질산화 미생물을 이용한 자원순환형 화장실에 대한 연구

February 2018

Graduate School of Seoul National University

Civil and Environmental Engineering

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Abstract

Study on the Resource Circulated Sanitation (RCS) Using Nitrifying Microorganisms

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Excretion is one of the most natural and frequent human biological processes that has existed since human beings first evolved. However, the lack of access to basic sanitation in many parts of the world makes it clear that current sanitation practices need to be improved. Accordingly, access to adequate and equitable sanitation and hygiene for all along with ending open defecation, as per the targets of the United Nations' Sustainable Development Goal Number 6 (SDG 6), are not possible using current sanitation systems.

A toilet is a sanitation fixture used for the disposal of human waste. It is a source of water consumption and wastewater production as well because it disposes of a mixture of human waste with water. Such a practice is not sustainable, as it has several challenges such as high water and energy consumption and complicated infrastructure to treat the mixture.

A vicious cycle of water and sanitation exists, i.e., without water supply, there is no proper sanitation, and without proper sanitation, water supply is reduced. Overcoming these problems is a critically important matter; thus, access to adequate and equitable sanitation and hygiene is identified as an essential

target of the SDG 6. Specifically, SDG 6.2 aims to end open defecation, paying particular attention to the needs of women and girls and those in vulnerable situations. Indicators of SDG 6.2 are defined as the proportion of the population using safely managed sanitation services, including a hand-washing facility with soap and water. These indicators are assigned without considering the availability of fresh water and capacity for treating the produced wastewater.

Consequently, a new paradigm of sanitation should be developed to address the global issues of sanitation as well as being considered as an indicator for SDG 6.2. Therefore, in this dissertation, a resource circulated sanitation (RCS) system is developed as a solution to the second target of the SDG 6.

RCS systems can notably reduce water and energy consumption by separating urine and feces from the source and treating them onsite to be utilized as fertilizer. Their maintenance procedure is very cheap and easy.

The system is usually containing three main parts; one is the seat which plays a vital role in the separation process. The remaining ones are urine and feces reactors which should be well designed to meet the condition for the final utilization purpose. All these parts have challenges including limitations for onsite treatments, and low social acceptability due to low cleanliness, odor, or compatibility with different cultures.

To solve such challenges scientifically, we are proposing our biological treatment method that is applied by separating urine from feces. Our method can optimize the fertility of source separated urine and feces to meet the criteria of a standard fertilizer as well as overcome other problems such as the odor of urine and high volume of feces.

We are also proposing a rainwater utilization method to mitigate urine scale formation and odor as essential challenges for maintenance of the RCS system. Utilization of rainwater can efficiently overcome the challenges. Thus we could optimize the amount of water supply which is consumed for maintenance purposes.

We have verified the efficiency of our designed RCS system in a field study by installing it in an urban farming center. Our study on the effectiveness of utilizing treated sanitary matters as fertilizer comparing with a local commercial fertilizer in cultivating white radish shows that the treated sanitary matters can be considered as a substitute for commercial fertilizer since the results of their application are quite compelling.

In conclusion, the key recommendation is that a sanitation revolution is required to contribute to achieving SDG 6 that considers human excreta a resource instead of waste, as learned from past sanitation practices.

Keywords: Nitrifying Microorganisms, Resource Circulated Sanitation, Sustainable Sanitation, SDG 6.

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1. Introduction

1.1. Background

As the human population grows, the intake capacity and overloading of the natural environment with emissions and waste are reaching a critical point. The main challenges are the consequences of inadequate drinking water sources and lack of sanitation facilities, which causes undeniable health and environmental problems especially water pollution (Langergraber and Muellegger 2005).

Worldwide, 884 million people lacked any drinking water service, and 2.3 billion people lacked any sanitation system while 892 million people worldwide are practicing open defecation (WHO/UNICEF 2017). International agreements are required to solve such global sever problems.

1.2. UN Millennium Development Goals

The Millennium Development Goals (MDGs) were the eight international development goals for the year 2015 that had been established following the Millennium Summit of the United Nations in 2000, following the adoption of the United Nations Millennium Declaration (UN 2000). The Target 7.C of MDG encourages that half of the people without access to safe drinking water and basic sanitation should have access by 2015 (UN 2000).

Consequently, in 2015, 4.9 billion people globally used an improved sanitation facility; 2.4 billion did not. Among those lacking adequate sanitation were 946 million people without any facilities at all, who continued to practice open defecation. Sixty-eight percent of the global population was using improved sanitation facilities compared to 59% in the year 2000. Hence, in 2015, 6.6 billion people, or 91% of the global population, used an improved drinking water source, versus 82% in the year 2000. Despite that improvement, an estimated 663 million people were using unimproved water sources or surface water that year. Moreover, not all improved sources are safe. For instance, in 2012 it was estimated that at least 1.8 billion people were exposed to drinking water sources contaminated with fecal matter (UN 2015a).

However, as the year 2015 ended and the world looked back at the progress that has been made, it became clear that while much has been accomplished, many of the goals of MDG 7 were not complete successes, and some failed outright. One of the noteworthy MDG 7 failures might be the fact that the success of the goals was not experienced equally across the globe which in itself is a significant defeat. Specifically, in the case of sanitation, trying to achieve MDG 7 through insufficient improvements of the conventional sanitation systems might have an undeniable role in the failure of MDG 7.

1.3. Concept of Waste-Oriented Sanitation

In most parts of the world, two options to tackle sanitation problems are applied which can be described as *drop and store* and *flush and forget* (Esrey et al. 2001). Such Waste-Oriented Sanitation (WOS) system is based on the perception of fecal material, which is considered as repulsive and not to be touched. The design of the technologies is furthermore based on the premise that excreta are wastes which are only suitable for disposal (Esrey et al. 2001, Langergraber and Muellegger 2005).

As presented in figure 1.1, water-borne sanitation as used in conventional sanitation systems is based on the collection and transport of wastewater via a sewer system, using (drinking) water as transport medium (Langergraber and Muellegger 2005, Lens et al. 2004). The system mixes comparatively small quantities of potentially harmful substances with large amounts of water, and the magnitude of the problem is multiplied.

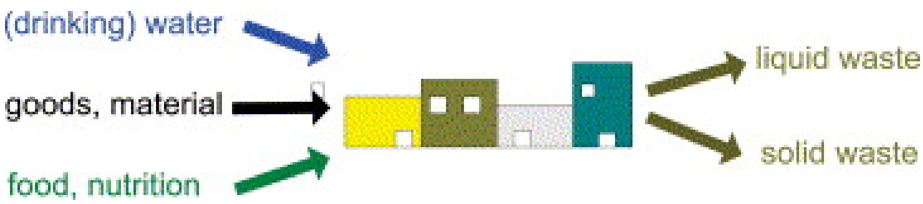

Figure 1.1. Linear Flows in a WOS System

Also, both the construction and operation and maintenance of the necessary hardware for WOS are a heavy financial burden. Even in developed countries, these conventional systems are directly cross-subsidized and the chances to ever become financially sustainable are low (Langergraber and Muellegger 2005).

1.4. UN Sustainable Development Goals

After the failure in achieving MDGs, the Sustainable Development Goals (SDGs) have been defined by the UN. SDGs, which are officially known as “Transforming our world: the 2030 Agenda for Sustainable Development”, is a set of 17 *Global Goals* with 169 targets among them (UN 2015b).

The 6th goal of SDGs is to ensure availability and sustainable management of water and sanitation for all(UN 2015b). The targets of SDG 6 are achieving universal and equitable access to safe and affordable drinking water for all as well as support and strengthen the participation of local communities in improving water and sanitation management (UN 2015b).

Specifically, SDG 6.2 aims to achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying particular attention to the needs of women and girls and those in vulnerable situations by 2030. The indicator of this item is the proportion of the population using safely managed sanitation services, including a hand-washing facility with soap and water (UN 2015b).

Accordingly, governments of different countries began to make efforts toward achieving the items of this goal. For instance, China launched a "toilet revolution" nationwide in 2015 to improve the toilet conditions as well as building new ones focusing on tourist sites. During the first three years of this plan, 68,000 toilets were built or renovated by investing more than 3 billion US dollars. According to a plan released by the China National Tourism Administration, until 2020, authorities aim to add 47,000 toilets and renovate 17,000 ones (Xinhua 2017). At the same time in India, Prime Minister Narendra Modi launched "Swachh Bharat" or the "Clean India" project. Among its targets is to make the entire country open-defecation free by 2019, with the construction of 12 million toilets with an initial government investment of about 190 USD for one individual toilet (Lu 2017).

However, the indicator is focused on the existence of WOS systems. Accordingly, only the availability of toilets and washing facilities are considered without noting the availability of fresh water as well as the treatment capacity of produced wastewater. Such indicator can increase the failure potential of achieving SDG 6.2.

Consequently, on the way from MDG 7 to SDG 6 to prevent the failures faced in achieving MDG 7, it is essential to define an innovative sanitation paradigm which can be well matched with the goal of SDG 6. Also, defining better indicators for SDG 6.2 is essential. In this dissertation, this new paradigm is being introduced as Resource Circulated Sanitation (RCS) system.

RCS system is developed based on the concepts of Resource-Oriented Sanitation (ROS) system in order to cover their limitations. Therefore, before introducing the concept of RCS, a review on the concept of ROS and its straight and weak points is essential.

1.5. Concept of Resource-Oriented Sanitation

The Resource-Oriented Sanitation (ROS) is an alternative approach to avoid the disadvantages of WOS systems. This innovative paradigm in sanitation is based on ecosystem approaches and the closure of material flow cycles (Han and Hashemi 2017, Langergraber and Muellegger 2005). Human excreta and water from households are recognized as a resource (not as a waste), which should be made available for recycling.

Reducing the public health risks related to sanitation, contaminated water, and wastewater, preventing the pollution of surface and groundwater, avoiding the degradation of soil fertility, and optimizing the management of nutrients and water resources are all examples for the advantages of ROS systems.

ROS represents a holistic approach towards ecologically and economically sound sanitation and is a systemic approach as well as an attitude. The applied technologies may range from natural wastewater treatment techniques to compost toilets, simple household installations to complex, mainly decentralized systems (Langergraber and Muellegger 2005). Therefore, ROS is not a low standard solution which is only applicable to poor people. It is more an appropriate solution for the different specific local situation (Han and Hashemi 2017).

1.6. Ancient Wisdom in ROS

Although the ROS is an innovative approach for western societies, its principles are not novel. In different Asian countries such as Korea, Japan, Vietnam, ancient sanitation systems were based on ecological principles which have been practicing for hundreds of years (Han and Hashemi 2017). While ROS systems are still acceptable in parts of east and southeast Asia, this option was primarily abandoned in western countries as WOS became the norm (Langergraber and Muellegger 2005).

Thus there has been a revival interest in ROS. For instance, in 2015, the movie Martian broadly showed the potential for growing potatoes on Mars using human feces (Han and Hashemi 2017). Such social approaches should be encouraged to increase public knowledge and acceptance.

1.7. Successful Implementation of ROS Systems

For the successful implementation of a ROS concept, a detailed understanding of all the components of the sanitation system is required.

For every local situation, the specific parameters have to be re-evaluated, always with the active involvement of the stakeholders (Langergraber and Muellegger 2005). Planning and decision-making processes should be participatory, by providing the users with information to enable an informed choice.

The experience of the failure of MDG showed that participatory planning process alone could miss a gender perspective of sanitation. Women and men, both should be involved because they benefit differently from improvements in sanitation. Thus, their demands and priorities are often not the same (Hannan and Andersson 2001, Langergraber and Muellegger 2005). Therefore, it is not enough to involve all stakeholders as one homogenous group, the different roles of women and men (and girls and boys respectively) have to be seen, and the various activities have to be adjusted (Hannan and Andersson 2001).

The technologies themselves have to be appropriate for the local and users' circumstances and should be flexible as well as affordable (Langergraber and Muellegger 2005). In such case, having frameworks based on local ancient wisdom can be very useful (Han and Hashemi 2017, Han et al.

2016). Different framework conditions, involved stakeholders, and motivating factors ensure that no two ROS projects are alike (Langergraber and Muellegger 2005).

1.8. Concept of Resource Circulated Sanitation

Although ROS is a very valid concept on the way toward SDG 6 and solving the sanitation problems sustainably, there are still essential challenges to be addressed. Most of the ancient wisdom of ROS systems are based on considering sanitary matters to be utilized as a fertilizer to increase the productivity of the society. Thus in most of ROS systems, there is lack of a sustainable and accessible treatment process to achieve a fertilizer which can be considered as a substitution with the currently available chemical and commercial fertilizers.

Accordingly, in this dissertation, a new concept of sanitation called Resource Circulated Sanitation (RCS) is being introduced which all its components are well designed to meet the final goal of production of fertilizer onsite sustainably as well as having a smooth maintenance procedure. The characteristics of RCS system and its technical, social and economic benefits yields its availability can be a much better indicator for SDG 6.2.

1.9. Structures and Objectives of Dissertation

Figure 1.2 presents the dissertation structure. In chapter 2, a review of the previous studies on WOS and ROS are presented while knowledge gaps are tried to be highlighted clearly.

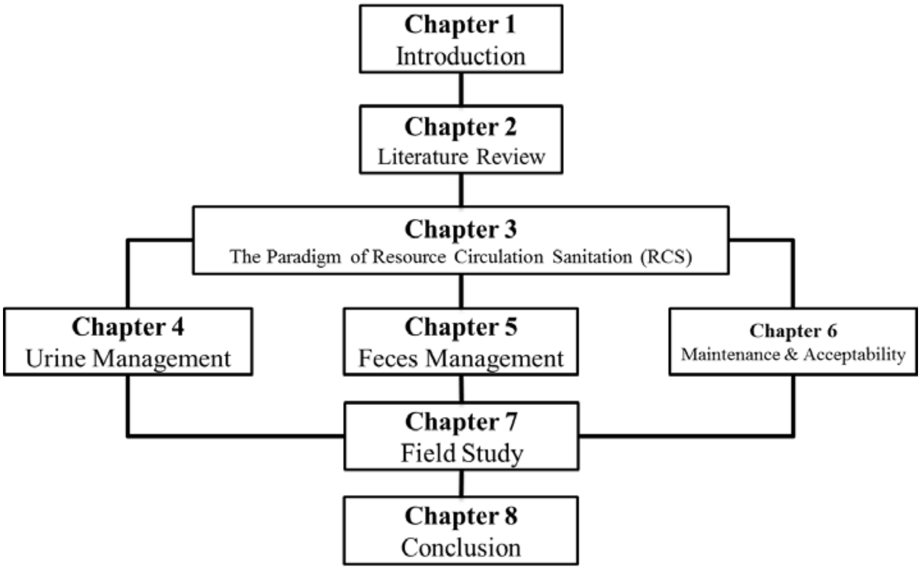

Figure 1.2. Structure of the Dissertation

Chapter 3 introduced the innovative paradigm of RCS and its characteristics. In this chapter, the challenges of RCS are discussed and explained that they can be overcome through scientific solutions. Chapters 4 to 6 are including the innovative solutions for urine, feces and maintenance management. Innovative biological approaches are introduced to optimize the treatment process of urine and feces as well as providing a sustainable maintenance. Chapter 7 describes the real site experience of RCS systems and presents how the products of RCS systems can compete with commercial fertilizers. Finally, chapter 8 the conclusions drawn from the described studies are compiled and summarized.

2. Literature Review

2.1. Waste Oriented Sanitation

The concept of using water for sanitation and hygienic purposes has changed dramatically in the past 50 years. Before that, the use of water-efficient apparatus in indoor facilities was not the norm. However, with the implementation of water policy use by local and governmental authorities the use of water-efficient apparatus started to increase (Shuaeb and Han 2018).

Toilet shares the most significant amount of water consumption and consequently the wastewater production in domestic wastewater. Water closets consume over than 50% of the daily uses inside residential buildings. For this reason, it was targeted to consume less by policymakers (Han and Hashemi 2017, Han et al. 2016). In 1992 as a country-wide plan to promote sustainability and energy efficiency the environmental protection agency (EPA) in the USA has issued an act that includes sections restricting toilet manufacturers from producing water closets that consume more than 6 liters per flush (LPF) (Shuaeb and Han 2018).

Nowadays, there are standards forcing toilet products to go through several tests to assure their eligibility to provide full extraction of waste and proper odor seal while consuming less than 6 LPF. For instance, the Australian standards also specify that the maximum flushing volume of water closets should not exceed 5.5 LPF and 6.3 LPF for dual flushing toilets (Han and Hashemi 2017, Jack 2000, Shuaeb and Han 2018).

On the other hand, the reduction of flushing water has caused problems in the toilet and inside the house drainage pipes. The reductions in flushing water lead to inadequate flushing and the need for the second flush (Han et al. 2016). Furthermore, the reduced amount of water in the toilet drain has reduced the ability to transport waste which leads to clogging and raised the cost of maintenance. These issues mainly occur in old drain pipes as they were designed to receive a higher amount of water (Littlewood and Butler 2003, McDougall and Swaffield 2000, McDougall and Swaffield 2007).

Also, the portions of waste to water have increased leading to what it is called nowadays by dry drains. These issues raised complain by end users and city officials and gave a bad reputation to low flush toilets. Currently, even certified toilet products by standards such as the mentioned above show a lack of performance and cause problems to the end users (Karadagli et al. 2009).

2.2. Studies on Resource-Oriented Sanitation

The working strategy and distinguishing feature in ROS are the concepts of source separation, split-stream collection and individual treatment of various wastewater fractions, viz. urine (yellow-water), fecal matter (brown-water), black-water (urine + feces) and grey-water (excreta-free household wastewater) (Simha and Ganesapillai 2017).

To allow the separation of these streams at the source, i.e., households, the technological solution employed is source separation or urine diversion through the use of a diverting toilet (Larsen et al. 2001). These toilets take advantage of human physiology which separately excretes feces and urine; the toilets are engineered to facilitate the collection of urine in a front end bowl and feces in the rear-ended bowl (Beal et al. 2008, Münch et al. 2009).

The rationale for source-separation seems obvious, at least in the present times as there is growing recognition that human urine, which contributes to less than 1% of the total wastewater volumetric flow accounts for more than 80% of the tot-N and more than half of its tot-P and tot-K (Esrey et al. 2001, Larsen et al. 2004, Vinnerås and Jönsson 2002).

Besides, a collection of the dry feces that contains most of the pathogens separate from the urine reduces the risk of potential transmission of water-borne diseases (Ashbolt 2004, Moe and Rheingans 2006). By elegantly preventing the mixing of these waste fractions diverting toilets, in essence, allow concentration of both nutrients as well as pathogens at the source.

The applicability and feasibility of diverting toilets as an alternative to conventional sanitation systems seem to be well established which is evident in the number of installations of diverting toilets across the world (Bongartz et al. 2010, Menter 2016, Münch and Winker 2009, Okem et al. 2013, Platzer et al. 2008, von Münch and Ingle 2012). Furthermore, based on suitability and adaptability of various options for Ecological Sanitation, for a given context, location and set of socio-economic and cultural circumstances, recommendations have already been put forward that allow the identification of an appropriate sanitation technology.

Detailed procedures are now available for the design, construction, installation, and use of various parts of the diverting toilet and the overall system. Besides, guidelines on safe source-separation, storage and re-use have already been published (Höglund 2001, Jönsson et al. 2004, Rieck et al. 2012, Schönning and Stenström 2004, Simha and Ganesapillai 2017).

2.2.1. Source Separation Procedures, the Gaps, and Challenges

Source separation and reuse of waste fractions have had to encounter and address several issues and may not be entirely ecologically-sound as we presume they were (Simha and Ganesapillai 2017). Human urine is a fast-acting liquid fertilizer that requires careful application and regulation. However, it has challenges such as causing volatilization of intrinsic ammonia (a greenhouse gas), increasing soil conductivity, salinity and pH; poor agro-productivity or in some instances, crop failures (Heinonen-Tanski et al. 2007, Heinonen-Tanski and van Wijk-Sijbesma 2005, Villa-Castorena et al. 2003).

Hu et al. (2016) recently emphasized this by observing that the use of organic liquid fertilizers would most likely lead to increased atmospheric emissions of ammonia resulting in acidification of soil and water.

More importantly, life cycle cross-comparisons with conventional WWTPs (Jönsson 2002, Tidåker et al. 2007) indicate that significantly large volumes of urine are required to provide a fertilizing effect equivalent to synthetic fertilizers.

A significant challenge in closing the sanitation cycle lies in the logistics of connecting farmers (nutrient sinks) with citizens (source of nutrients) that use decentralized (in some cases, semi-decentralized) sanitation systems; in trying to provide the farmers with homogenized and standardized fertilizer products (Starkl et al. 2015) that ensure sustained reproducibility of crop yield enhancements.

Also, UDTs are connected to tanks that store around 300-500 L of urine. During pipe transport and storage, bacterial urease catalysis the hydrolysis of intrinsic urea. A further concern in UDTs is cross-fecal contamination of the relatively sterile and source-separated urine. Inactivation studies with urine point towards significant pathogenic risk due to the persistence of, among others, fecal sterols, *Enterococcus*, *Escherichia coli*, *Salmonella*, helminth ova such as *Ascaris*, rotavirus and bacteriophages (Höglund et al. 2002, Nyberg et al. 2014, Sundin et al. 1999, Winker et al. 2009).

In a study that analyzed 15 different storage tanks in Sweden and Australia, fecal sterols were found to cross-contaminate 22% of the samples in the upper portion and 37% of the samples from the sludge (Schönning et al. 2002). Nyberg et al. (2014) argue that microbial persistence also extends to the application of excreta in soils which creates further disease transmission pathways.

Due to these factors, the WHO (2015) recommends that, for production and raw consumption of crops, urine has to be stored for at least six months ($T > 20°C$) before application to ensure a high level of pathogen inactivation. Besides, the quantification, behavior and potentially harmful effects of micro-pollutants and pharmaceutical residues in source-separated human urine are not well understood.

In light of this scientific uncertainty, Larsen et al. (2004) invoke the precautionary principle over-application of fertilizer products from ROS systems. Even if we choose to not consider the sociocultural inhibitions against the use of human excreta which Jewitt (2011) observes to be a distinct aspect hindering the spread of ROS, there appear to be other fundamental concerns concerning the technology and system design aspects of ROS systems. As the narrative adopted here elucidates, these flaws in system design have stalled the proliferation of nutrient recycling.

Nonetheless, ROS does provide an efficient way to separate, collect and concentrate products that we require (nutrients) and those that we wish to regulate (pathogens, micro-pollutants, heavy metals) (Han and Hashemi 2017, Han et al. 2016, Simha and Ganesapillai 2017).

2.2.2. Technologies for Nutrient Recovery

Over the last decade, the research focus in ROS has shifted from studies that validate the potential of human excreta for fertilization to studies that identify and realize the recovery of nutrients and resources from source-separated human excreta.

Since we consider ROS itself to be an alternative paradigm, this change in the devotion of research efforts by the scientific community appears to be a paradigm shift within a paradigm shift as it represents a change in emphasis from "split-stream collection and reuse" to "split-stream collection, resource recovery and safe reuse" (Simha and Ganesapillai 2017).

By simultaneously mapping the chemical/nutrient composition of various potential fertilizer products from eco-sanitation systems against their suitability for production of crops, Winker et al. (2009) illustrate how urine is the most promising and well-investigated product from such systems.

Several investigations have reported the development of technologies that can safely harness nutrients from human urine to yield usable end products (Dodd et al. 2008, Ganesapillai et al. 2015, Ganrot et al. 2007, Kujawa-Roeleveld and Zeeman 2006, Maurer et al. 2006, O'Neal and Boyer 2013, Pronk and Kone 2009, Udert and Wächter 2012, Zhang et al. 2014).

An approach favored by many researchers has been struvite precipitation where significant P and some N as has been recovered (Ban and Dave 2004, Ganrot et al. 2007, Höglund et al. 2000, Kemacheevakul et al. 2011, Lind et al. 2000, Ronteltap et al. 2007). However, the process is contingent on the external addition of Mg which elevates the pH, reduces the solubility of PO_4^{3-}, induces supersaturation and spontaneous precipitation (Wilsenach et al. 2007).

Nevertheless, as Etter et al. (2011) note, the recovery of ammonium through struvite precipitation may be only 5%, and other macronutrients may not be recovered. Technologies used in water treatment have also found application in nutrient recovery from urine. For instance, Dodd et al. (2008) demonstrated the ozonation of hydrolyzed urine for nutrient recovery which also allowed depletion of indicator micropollutants. Through adsorption procedures, Ganesapillai et al. (2015) recovered urea using coconut shell based activated carbon while Lind et al. (2000) used clinoptilolite and wollastonite for nitrogen fixation after been performed as standalone or with other operations such as absorption, struvite precipitation, evaporation, etc. (Maurer et al. 2006).

Dewatering hydrolyzed urine by forwarding osmosis was demonstrated by Zhang et al. (2014) although N recovery from this process is imperfect. Recently, biological nitrification in combination with alkaline stabilization and distillation as investigated by Udert and Wächter (2012) illustrated near complete recovery although process energy requirements were found to be 4-5 times of conventional wastewater treatment. Other advocated technologies studied include volume reduction through freezing-thawing (Lind et al. 2000) as well as drying (Antonini et al. 2012), ion-exchange with targeted P recovery (Beler-Baykal et al. 2004, O'Neal and Boyer 2013) and anaerobic treatment (Kujawa-Roeleveld and Zeeman 2006).

The analysis of the literature on nutrient cycling illustrates that, although ecological considerations have influenced these technologies, they demonstrate variable efficiency in recovery of the primary nutrients (N, P, and K) from urine. Since many of these processes have been engineered to optimize specific parameters they fail to provide integrated nutrient recovery; in their review of existing technologies, Maurer et al. (2006) reiterates this observation. For instance, N removal through struvite precipitation is relatively weak in comparison to the recovered P (Lind et al. 2000); persistent pathogen build-up has been recognized in the precipitated struvite despite post-separation air drying of the cake (Decrey et al. 2011).

Recently, Ishii and Boyer (2015) also stressed the need for continued research on nutrient recovery technologies beyond struvite precipitation. Besides, in an audit of 12 toilet designs (with and without urine diversion), Starkl et al. (2015) observed that decentralized treatment processes such as anaerobic digestion, dehydration, and composting have proven to be insufficient and invariably necessitate significant user maintenance.

Furthermore, with regards to the concentration of pharmaceuticals and micro-pollutants, it would be prudent to consider that human urine contains far lesser concentrations of these compounds than wastewater or farm manure and excreta (Winker et al. 2008). Moreover, as Rehman et al. (2015) observe, the most significant contribution (hence, risk) of active pharmaceuticals to the environment stems from the pharmaceutical industry itself; this is especially true for densely populated developing countries where pharmaceutical production has grown tremendously but not commensurate with efficiency or extent of effluent treatment.

Indeed, Larsson et al. (2007) demonstrated that treated effluent from a wastewater plant that served 90 (bulk) drug manufacturers in Hyderabad, India contained the highest level of pharmaceuticals reported in any effluent with detected levels of ciprofloxacin (28-31 mg/L) exceeding levels of EC_{50} toxicity for bacteria by orders of magnitude. There is concern of enhanced risk from the development of antibiotic resistance in pathogens as the treatment plants operations involved mixing human sewage with the drug manufacturer's effluents which only goes to substantiate the case for implementing diversion-based decentralized sanitation systems which at the very least allow localized concentration of pollutants that we wish to target and eliminate (Simha and Ganesapillai 2017).

Of course, this also begs the question as to why ROS systems must be judged against standards of treatment that current centralized treatment plants themselves do not meet. While not advocating for relaxing regulations for ROS systems or setting a lower benchmark, it makes a point towards factors such as institutional resistance against changes to conventional systems.

More importantly, concerns over active substances provide further opportunities for researchers working with ROS systems to ensure that post-diversion processes are compliant with regulatory requirements.

Hence, the realization of a closed loop sanitation system that aspires to reutilize human urine hinges considerably over post urine diversion operations. It is in these steps that there lies an opportunity for substantial value creation (through the processing and production of urine-based fertilizers) as well as risk minimization (through pathogen inactivation and micro-pollutant elimination). While we tend to reduce these risks through the provisioning of (urine-diverting) toilets, for us to contain and eliminate them, continued research effort to envision and implement integrated nutrient recovery technologies.

To accelerate the proliferation of urine diversion and adoption of decentralized sanitation system, we believe that, it is imperative for us to devise integrated technological pathways for post-urine diversion operations that simultaneously provide near-complete nutrient (N, P, and K) recovery, pathogen elimination and reduction of pharmaceuticals and active substances in line with regulatory requirements.

2.3. The Impact of this Dissertation

Among the literature, which is reviewed as above, there are lacks three essential items as below:

1. The idea of utilizing the nitrifying microorganisms to control the nitrogen composition in separated urine and feces.
2. To optimize the sanitary matters to meet the standard criteria for fertilizer.
3. Control of odor, especially for urine, as an essential maintenance action.

Working on the items above was a notable motivation for this dissertation. Moreover, by introducing the RCS as an innovative sanitation system having higher efficiency, it might be possible to consider it as a substitute to WOS, making a better indicator for measuring the progress in achieving the targets of SDG 6.2.

3. The Paradigm of Resource Circulated Sanitation

3.1. Introduction

Excretion is one of the most natural and frequent human biological processes that has existed since human beings first evolved. However, as it is explained in previous chapters, the lack of access to basic sanitation in many parts of the world makes it clear that current sanitation practices need to be improved (Han and Hashemi 2017). Accordingly, adequate and equitable access to clean water and sanitation for all, per the sixth item of the United Nations' Sustainable Development Goals (SDGs), is not possible using current sanitation systems and a new paradigm is required.

In this chapter, different sanitation practices that have been used throughout history are reviewed and compared based on water consumption, wastewater generation, and resource utilization. The Resource Circulated Sanitation (RCS) and its characteristics are introduced to be as an ideal sanitation practice which uses no (or less) water, considers excreta a resource, as has been practiced in East Asian countries for thousands of years, and has a smooth maintenance procedure. Accordingly, research trends and ways to overcome cultural and technical barriers are introduced and suggested.

3.2. Sanitation Practices throughout History

Since the beginning of humankind, eating and excreting have been an essential part of life. Therefore, varying sanitation practices might have developed because of different natural conditions, such as geography and climate, as well as economic backgrounds, creating distinct cultures and traditions (Hashemi et al. 2015c).

Figure 3.1 presents the development of sanitation practices over time. Next, each system is described and evaluated regarding water consumption, wastewater production, and resource utilization (Han and Hashemi 2017).

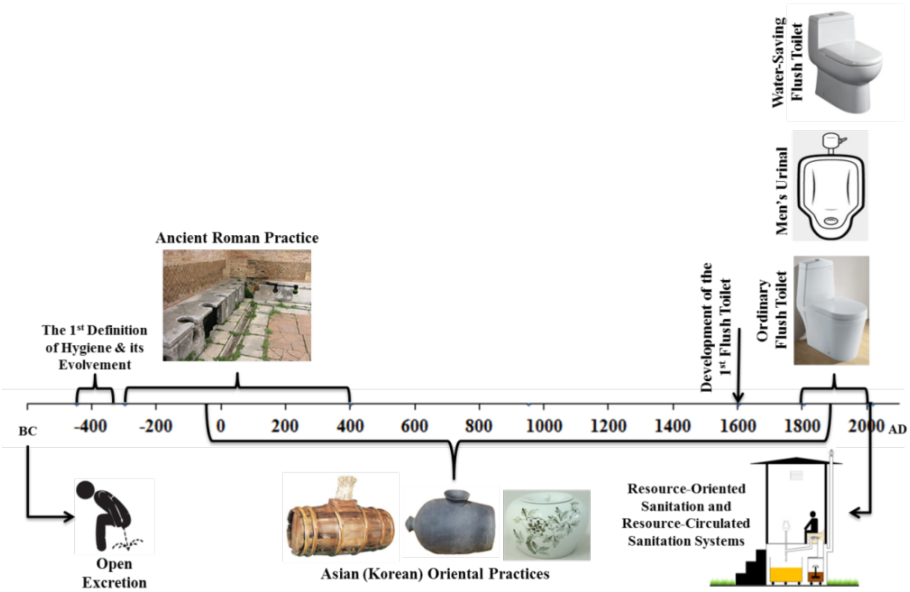

Figure 3.1. Development of Sanitation Practices throughout History

3.2.1. Open Defecation

Open excretion is the oldest excretion practice (Bracken et al. 2007, Han and Hashemi 2017) and is still used in some parts of the world. As the population increased and advanced, humankind felt the need to reduce its contact with sanitary waste to live longer comfortably (Bracken et al. 2007, Han and Hashemi 2017). No water is consumed in open excretion, and the only wastewater produced includes urine, feces, or a mixture of the two.

Consequently, for a controllable amount of excretion, it can be used as fertilizer; however, as the volume of excretion increases due to urbanization, water bodies including groundwater become contaminated.

3.2.2. Oriental Sanitation Approaches in Western Societies

Between 460 – 377 BC, during the time of Greek physician, Hippocrates, the first definition of hygiene appeared and evolved (Aiello et al. 2008). During 300 BC-AD 400, the system of aqueducts was built and developed in Ancient Rome (Aiello et al. 2008). People used to excrete over channels, in which water was running (Han and Hashemi 2017, Mattelaer 1999). In these systems, waste was transported to and dispatched in free water bodies such as rivers and seas (Bracken et al. 2007, Han and Hashemi 2017, Mattelaer 1999). Therefore, water was used to remove sanitary matter, leading to the production of wastewater. This wastewater was dispatched into nature without any specific treatment nor intention for use as fertilizer.

3.2.3. Oriental Sanitation Approaches in Asian Societies

Overlapping with the latter half of the sanitation development period in Ancient Rome, sanitation practices began in Asia as well (Bracken et al. 2007, Han and Hashemi 2017, Han and Kim 2014). For example, in Korea, in a period from the Silla dynasty to the Joseon dynasty (57 BC – 1897 AD) people understood that excreta could be utilized as fertilizer (Bracken et al. 2007, Han and Hashemi 2017, Han and Kim 2014, Hoyt 1972).

In ancient Korean societies, it was well known that urine and feces could enhance land fertility if kept separate from each other and water.

Accooordingly, Korean temple toilets were designed to deposit the feces into well-ventilated compost chambers. The feces was then removed from the bottom of these chambers and used directly as fertilizer (Han and Hashemi 2017, Han and Kim 2014, Hashemi et al. 2015c). Additionally, ancient Koreans were familiar with source separation, and they had unique instruments to separate and manually transport the excreta (Han and Hashemi 2017, Han and Kim 2014, Hashemi et al. 2015c).

At that time, using a yogang (urine jar), which was usually situated near a room for easier access, was common. The collected urine waste was fermented to serve as agricultural fertilizer. Furthermore, the different fermentation stages of urine were made possible by using several urine jars, which were stored in an organized fashion. Farming equipment, known as ojum-janggun (urine jar) and ddong-janggun (feces jar), were used to carry separated urine and feces, respectively. By these practices, urine and feces were collected separately without dilution, later to be utilized as fertilizer (Bracken et al. 2007, Han and Hashemi 2017, Han and Kim 2014, Hashemi et al. 2015c).

The same practices were typical in middle and East Asian countries such as China, Vietnam, and Japan (Bracken et al. 2007, Han and Hashemi 2017, Han and Kim 2014, Hoyt 1972, Needham and Lu 1959). For these practices, water was not consumed nor was wastewater produced, and all sanitary matter served as a nutrient resource via utilization as fertilizer.

3.2.4. Flushing Toilets

In 1596, toilets with flushing function were invented, and in the 19th and 20th centuries, modern sewer systems were developed and constructed in many European and US cities, initially discharging untreated sewage to waterways (Bracken et al. 2007, Mattelaer 1999).

When the discharge of untreated sewage became increasingly unacceptable, experimentation towards improved treatment methods resulted in different advanced treatment practices, and ordinary flush toilets and men's urinals became common at that time (Mattelaer 1999). These systems are based on water and, apparently, consume water and accordingly produce wastewater, which undergoes the advanced treatments.

However, these treatment processes still are not sufficient and send partially treated waste to natural water bodies, which transfers contaminants such as pharmaceuticals, personal care products (PPCP), endocrine disrupting compounds (EDC), and micro-pollutants into the water resources (Han and Hashemi 2017, Han and Kim 2014, Hashemi et al. 2015c). Except for limited utilization of treated sewage sludge as a resource for energy production, there is no systematic treatment process considered for an aimed utilization (La Berge 2002).

3.2.5. Water-Saving Toilets

After the appearance of MDG 7 with the aim of improving sustainable access to safe drinking water and basic sanitation, several trials were performed to modify the flushing function of toilets and reduce the water required for flushing (Han and Hashemi 2017, La Berge 2002). At this stage, water-saving toilets and urinals were produced (La Berge 2002). Furthermore, there were trials for developing sanitation practices with minimum water and energy consumptions, such as waterless urinals and composting toilets (Han and Hashemi 2017, Tilley et al. 2014).

3.2.6. Resource-Oriented and Resource Circulated Sanitation Systems

Recently, resource-oriented sanitation (ROS) practices are being developed, which are receiving increased attention after the definition of SDG 6 (Han and Hashemi 2017). These systems, which are also understood as sustainable or ecological sanitation, are enabling nutrient reuse, mainly by source separation and covering a full range from high- over medium- to low-tech and from decentralized to centralized solutions (Han and Hashemi 2017). The Urine-Diverting-Dry-Toilets (UDDTs) can be a good example for these systems, which are based on minimum water consumption, for hygienic purposes such as hand washing and anal cleansing, and accordingly minimum wastewater production, which usually can be treated in-situ, as well as source separation of urine and feces and the utilization of such after treatment.

However, ROS systems are practically limited to the storage of urine and feces separately which have lack of a systematic onsite system to have a proper treatment process for further recycling aims such as being utilized as fertilizer. Therefore, developing a new paradigm as RCS systems is essential for a favorable trend toward SDG 6.

3.3. Characteristics of RCS Systems

As presented in figure 3.2, all RCS systems contain three central concepts as:

1. Toilet seat and men's urinals as well as facilities for handwashing and in-situ treatment of the produced gray water. This section is flexible and can be modified based on the users' sanitation and cultural requirements.
2. Urine treatment and disposal system to be recycled as fertilizer.
3. Feces treatment and disposal system to be recycled as a soil conditioner.

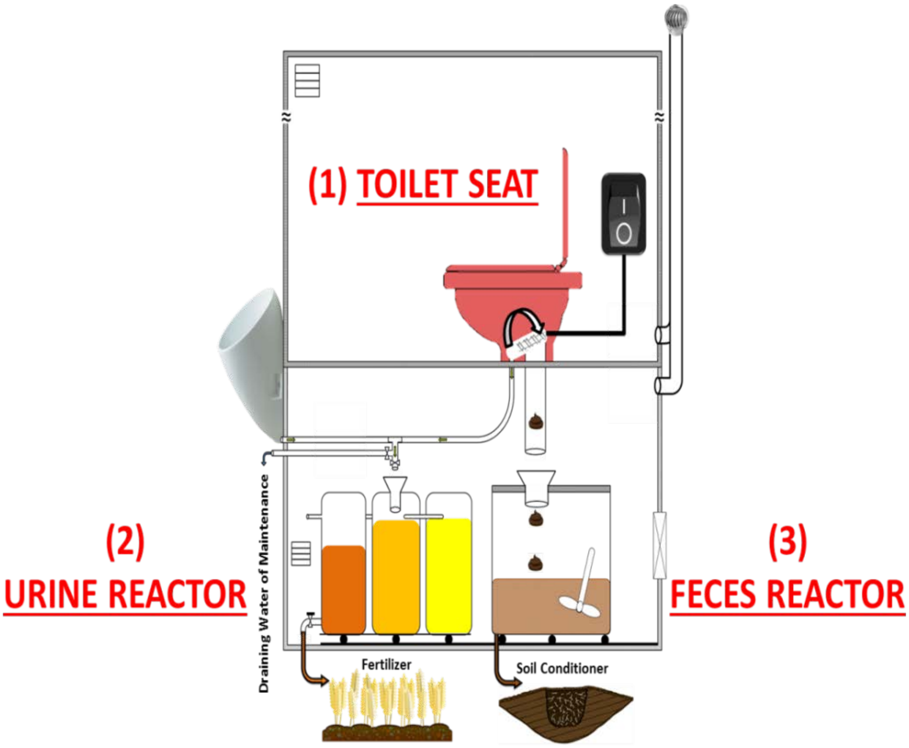

Figure 3.2. Characteristics of RCS Systems

Each of the characters above should be designed properly to have a smooth and sustainable maintenance. The upper part should be safe, attractive and secure to use while the downer part requires a scientific way forward. In this case, there are essential challenges which should be overcome.

3.4. Research Trends in RCS

Although RCS systems, with mentioned characteristics, are potentially environmentally friendly sanitation practices, they have challenges to be overcome (Han and Hashemi 2017). Similar to any other sanitation systems, the potential costs for developing countries, cleanliness, and proper maintenance are critical challenges that should be managed to achieve higher public acceptability.

First of all, although several scientific studies are showing the high potential of human excreta to be utilized as good fertilizer to produce more food (Esray 2001, Han and Hashemi 2017, Han et al. 2016), there is a gap in public knowledge, and many people nowadays do not understand the concept. Furthermore, there are several cultural barriers such as necessitating water consumption in sanitation practices in some religions (Hashemi et al. 2015b). There are several research opportunities and approaches for investigating solutions for these challenges. For improving social acceptability, educational, cultural activities are required. For instance, in 2015, the movie Martian broadly showed the potential for growing potatoes on Mars using human feces (Han and Hashemi 2017). Such social approaches should be encouraged to increase public knowledge and acceptance.

Technically, high-efficiency separation is the first essential step that should be functional at all times including for cases such as diarrhea. Urine scale formation and odor are two critical challenges, which lead to bottlenecking, making full acceptance of RCS systems impossible in a decentralized wastewater system. In such cases, proper operation and maintenance (O&M) management are required. Furthermore, a certain amount of water should be available for other hygienic processes such as hand washing and anal cleansing and the gray water that is produced from such should be treated and recycled in-situ which can also satisfy the obligation of water consumption in some cultures (Hashemi et al. 2015b).

The separately stored sanitary matter must be treated to be utilized as fertilizer. In this case, the treatment processes should be designed based on the quantity and characteristics of the sanitary matter as well as on consideration of the economic aspects, including costs and benefits of the system. Advances in these concepts can significantly increase the efficiency and acceptability of RCS systems as substitutions for the current unsustainable practices. In further chapters, our solutions for the mentioned challenge of urine and feces management as well as a sustainable maintenance are presented.

3.5. Conclusions

In this chapter, different sanitation practices throughout history have been reviewed. Some practices consider human excreta as waste, whereas others consider it as a potential resource. It is noteworthy to see some of the old practices in East Asia, which consume no water and use the excreta as fertilizer instead of considering it a waste. This concept can be a model for a sustainable solution toward SDG 6. However, some cultural, as well as technical barriers, exist. Research on trends and ways to make sanitation processes more aesthetical and efficient are in progress in the science and technical fields.

For achieving the goals of SDG 6 and 6.2, a revolution of sanitation is required based on an innovative sanitation paradigm called RCS, in which human excreta is considered a resource instead of waste by learning from past practices of sanitation. In upcoming chapters, our solutions for RCS technical challenges are presented.

4. Urine Management

4.1.Introduction

Urine has been collected and used as fertilizer in different parts of the world (Han and Kim 2014, Hashemi et al. 2015b, Hashemi et al. 2015c). Early Koreans practiced urine collection in special containers called “ojum-janggun” and utilized the urine (Han and Hashemi 2017, Han and Kim 2014). This is because in ancient times, people had empirical knowledge of the high concentration of nutrients in urine, such as nitrogen (N), phosphorus (P), and potassium (K) compounds, which makes it a good fertilizer (Han et al. 2016, Han and Kim 2014, Hashemi 2015).

Among the nutrients in urine, the nitrogen (N) profile changes with time, owing to chemical reactions among different compounds such as ammonia, ammonium, nitrite, and nitrate, whereas phosphorus (P) and potassium (K) compositions do not undergo significant changes (Hashemi et al. 2016, Kirchmann and Pettersson 1994). Therefore, to optimize the utilization of urine as a fertilizer, studies of the changes in nitrogen profile in source-separated urine are required. Furthermore, using solid additives to harvest nutrients from urine can also be a beneficial way to make fertilizer from urine.

In this chapter, first, a biological approach for modifying nitrogen composition of urine through nitrifying microorganisms is studied. Then nutrient harvesting process through adding rice straw powder is investigated.

4.2. Optimization of Fertilization Characteristics of Urine by Addition Nitrifying Microorganisms Bio-seed

4.2.1. Chemical and Biochemical Background

The concentration of ammonium and nitrate in urine depends on the chemical reactions involving ammonia. However, because of the high pH of stored urine, ammonia is released as gas; not only is this the main reason of urine odor, but it also suggests a loss of nutrients (Hashemi et al. 2016). Thus, it is essential to maintain ammonia in the dissolved form in the urine.

Although plants absorb nitrogen as either nitrate or ammonium, high concentrations of nitrate in a fertilizer can damage soil and plants (Savci 2012). The European Commissions (EC) standards state that the ratio of ammonium (NH_4^+) and nitrate (NO_3^-) in a nitrogen fertilizer should be 1:1 for it to be identified as a standard fertilizer (European Commission 2003). Therefore, the purpose of nitrogen control in urine is to reduce nitrogen loss while maintaining equal concentrations of nitrate and ammonium. To this end, nitrifying microorganisms can be utilized, as they can accelerate the changes in nitrogen composition via biochemical reactions such as nitrification.

However, although the general effect of nitrifying microorganisms on urine has been investigated in recent studies such as that by Maurer et al. (2006), only limited studies have shown the optimization of the nitrogen profile in urine by using microorganisms.

Figure 4.1 presents the characteristics of pure fresh urine in a simple way. It typically contains 95% water, 3.8% urea and 1.2% minerals. As soon as urine is excreted from the human body, urea is converted to ammonia by the enzyme urease, via the reaction presented in equation 4.1:

$$CH_4N_2O + H_2O \rightarrow 2\ NH_3 + CO_2 \qquad \text{(Eq. 4.1).}$$

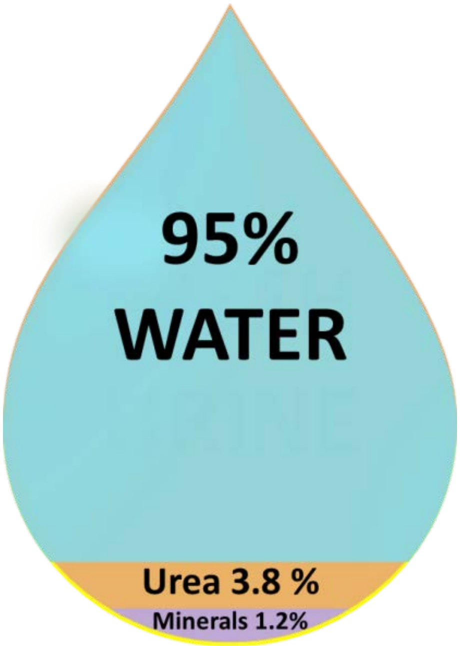

Figure 4.1. Simplified Schematic of Characteristics of Pure Fresh Urine

However, at a pH of > 9.22, as in the case of pure urine, the major compound formed is ammonia, which dissolves in water by forming hydrogen bonds with water molecules (Hashemi et al. 2016), as well as producing ammonium, as shown in equation 4.2:

$$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-,\ K_b = 1.8 \times 10^{-5} \qquad \text{(Eq. 4.2).}$$

Because of evaporation and higher electronegativity of oxygen than nitrogen, the hydrogen bonds between ammonia and water molecules easily break, and ammonia is released as gas (Hashemi et al. 2016). This is not desirable, as it not only reduces the amount of nutrients but also produces odor.

Nitrification is the process of conversion of ammonium into nitrite and then into nitrate, which is commonly carried out by two separate groups of microorganisms (Texier et al. 2012). However, the latter has lower free energy change values which means that oxidation of ammonium is the primary step in which ammonium-oxidizing microorganisms such as *Nitrosomonas Europaea (N. europaea)* obtain energy (Texier et al. 2012). By nitrification, the concentration of NH_4^+ is reduced, and more NH_3 would be converted to NH_4^+. This process, which also reduces the pH, shifts the equilibrium of equation 4.2 to the right, thereby decreasing gaseous ammonia release. Thus, by adjusting the nitrification process, we can optimize the concentration of nitrogen compounds.

4.2.2. Materials and Methods

Pure urine samples were collected from men's waterless urinals designed for research purposes installed in Building No. 35 of Seoul National University. A microbial bio-seed solution containing 6×10^6 *N. europaea* cells/100 mL was prepared by GnV Company, located at Gunpo City, Gyeonggi Province, Republic of Korea. The bio-seed solution includes various microbial growth promoters including amino acids and vitamins. *N. europaea* was used, as it is known to be capable of degrading a variety of organic compounds, which may make it suitable to be used as an additive for improving fertilization characteristics of urine (Chain et al. 2003). Initial characteristics of urine are presented in Table 1.

Table 4.1. Initial Nitrogen Profile of Pure Urine

pH	**Initial Nitrogen Compound Concentration (mg/L)**			
	Total Nitrogen	**Ammonia**	**Ammonium**	**Nitrate**
9.82	6624.59	4504.72	1722.39	264.98

A 1-L beaker filled with urine was used as an open-batch bioreactor. Pure urine was used immediately for the experiment. Different volumes of bio-seed solution (5–15 mL for 1 L urine) were added, and the mixture was stirred, but subsequently, no mixing was done throughout the experiment.

Total nitrogen, NH_3, NH_4^+, and NO_3^- were quantified every day at a constant temperature of 15 °C, using UV/Visible Spectrophotometer Model HS-3300, and the pH was measured using Aquaread Aquaprobe model AP–2000. This temperature was chosen because it is the mean of commonly used temperatures in the source-separated urine tank (Höglund 2001), and nitrification by *Nitrosomonas* is not affected significantly at a temperature of 15–20 °C (Zhu and Chen 2002). All measurements were made according to the US EPA standards (USEPA 1979).

Samples were prepared in 100-mL glass tubes and left in a Cole-Parmer Standard Benchtop Chilling/Heating Block, model 100–230 VAC equipment to attain constant temperature. Samples for measurement of chemical concentrations were taken while the stock samples were still in the chilling/heating block. The nitrogen loss at each time interval was considered as the difference between measured total nitrogen at that interval and that at the previous interval, whereas the difference of total nitrogen compared to the sum of all compounds that are measured separately has been taken as the concentration of other nitrogen compounds.

Experiments were performed in triplicate, and the arithmetic means of the measured values were taken as the final data. The measurement procedure continued for 30 days; however, we found that the composition of nitrogen compounds in all samples did not change significantly after 15 days.

4.2.3. Results and Discussion

4.2.3.1. Changes in Nitrogen Profile of Pure Urine

Figure 4.2 shows how the nitrogen profile of pure urine changed with time. The results show about 30% nitrogen loss. The pH of stored fresh urine was observed to increase rapidly and became constant at 9.8. At such high pH, the concentration of ammonium decreases, as it is converted to ammonia, according to equation 4.2.

Thus, to improve the fertilization characteristics, nitrogen loss should be minimized, while maintaining the nitrate:ammonium ratio at approximately 1:1. The nitrogen profile of stabilized urine can meet the nitrate:ammonium ratio requirement, but there is high nitrogen loss, which leads to more smell production; this hinders the utilization of urine as fertilizer.

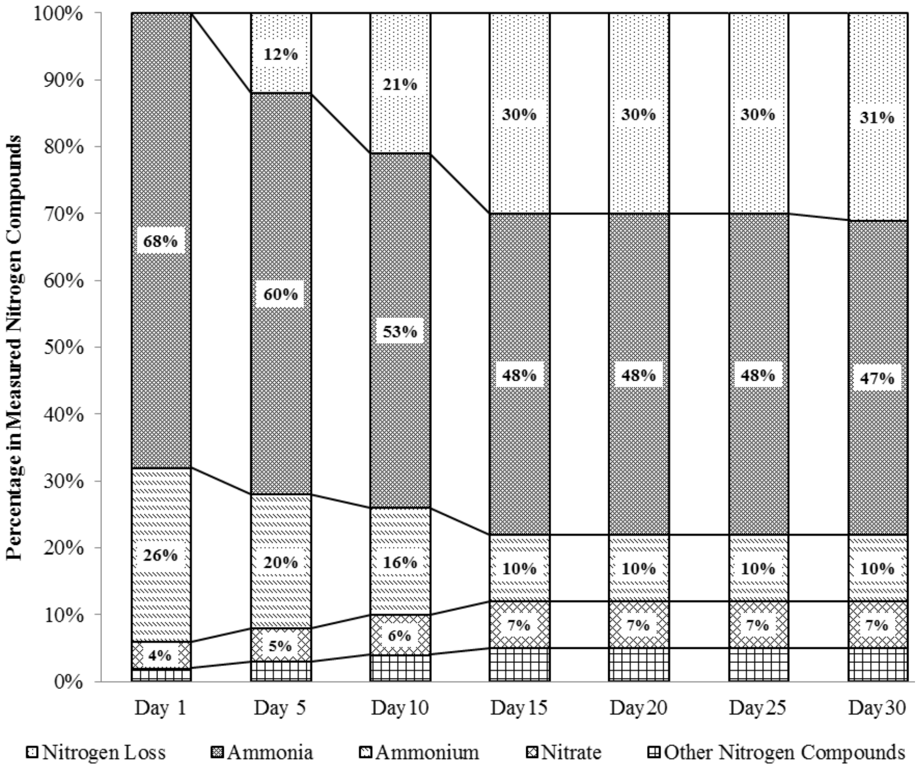

Figure 4.2. Changes in Nitrogen Profile versus Time in Pure Urine

4.2.3.2. Effect of **N. europaea** *Bio-seed on the Changes in Nitrogen Profile*

Figure 4.3 shows the stabilized nitrogen profile in urine by using different concentrations of bio-seed. According to the results, in the sample with 6×10^5 *N. europaea* cells/L, nitrogen loss was approximately 11%, which means that nutrient reduction and odor production were approximately three times lower than that in urine without added bio-seed. Furthermore, the 1:1 ratio of nitrate:ammonium conforms to the EC standards and regulations for fertilizers.

In other samples (e.g., the sample with 9×10^5 *N. europaea* cells/L), although there was lower nitrogen loss as compared to pure urine, nitrate was the significant part of the nitrogen composition, which can cause pollution and over-fertilization.

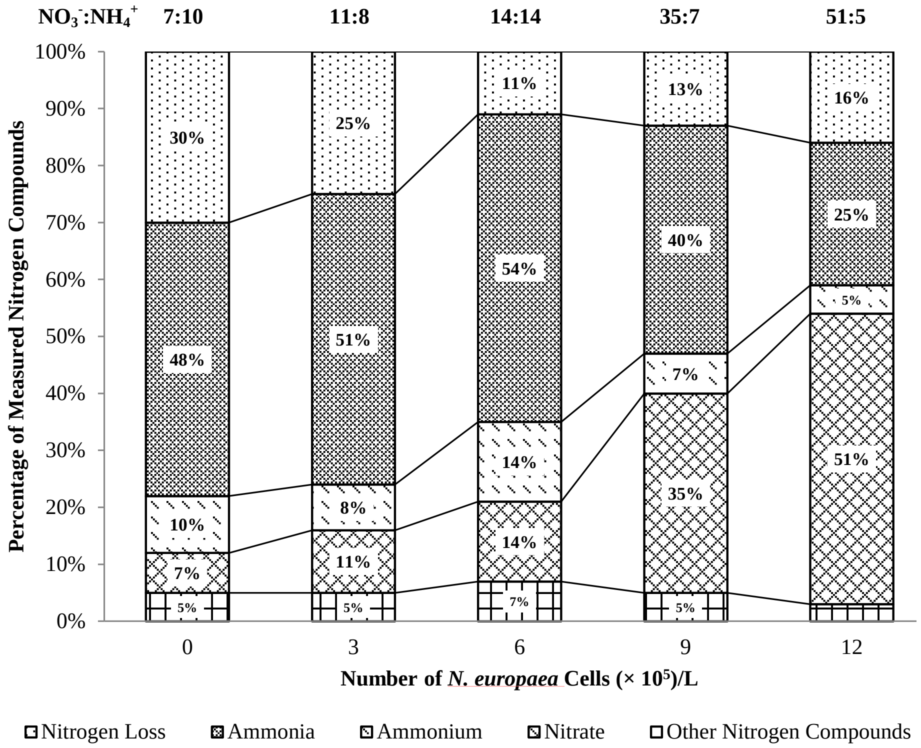

Figure 4.3. Stabilized Nitrogen Profile after Adding Different Concentrations of *N. europaea* Bio-seed

Nitrification by *N. europaea* depends heavily on pH. Grady Jr et al. (2011) stated that the optimal pH range is 7–8. As shown in Figure 4.4, the stabilized pH of the samples after 15 days is about 8–10, which is not within the optimum range for nitrification by *N. europaea*.

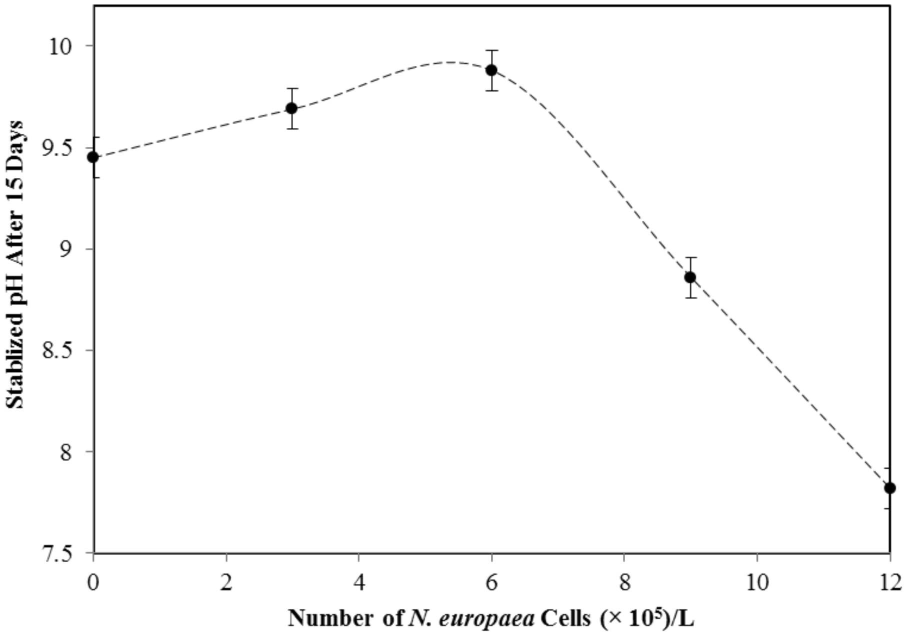

Figure 4.4. Stabilized pH in Samples with Different Bio-seed Concentrations

Addition of bio-seed at a concentration of 6 × 10^5 cells (10 mL bio-seed in 1 L urine) increases the pH, which represents a very weak nitrification process. This weak nitrification produces less NO_3^- but a high concentration of NH_3, which is stabilized within a shorter duration. Further addition of bio-seed increases bacterial activity, leading to increased NO_3^- production and a subsequent pH reduction.

4.2.3.3. Optimum Concentration Range of **N. Europaea** *Bio-seed for Optimization of Fertilization Characteristics*

Figure 4.5 shows the percentages of nitrogen loss at different *N. europaea* bio-seed concentrations and durations. This graph suggests that the lowest amount of sustained nitrogen loss occurred at a bio-seed concentration of approximately 6 × 10^5 *N. europaea* cells/L.

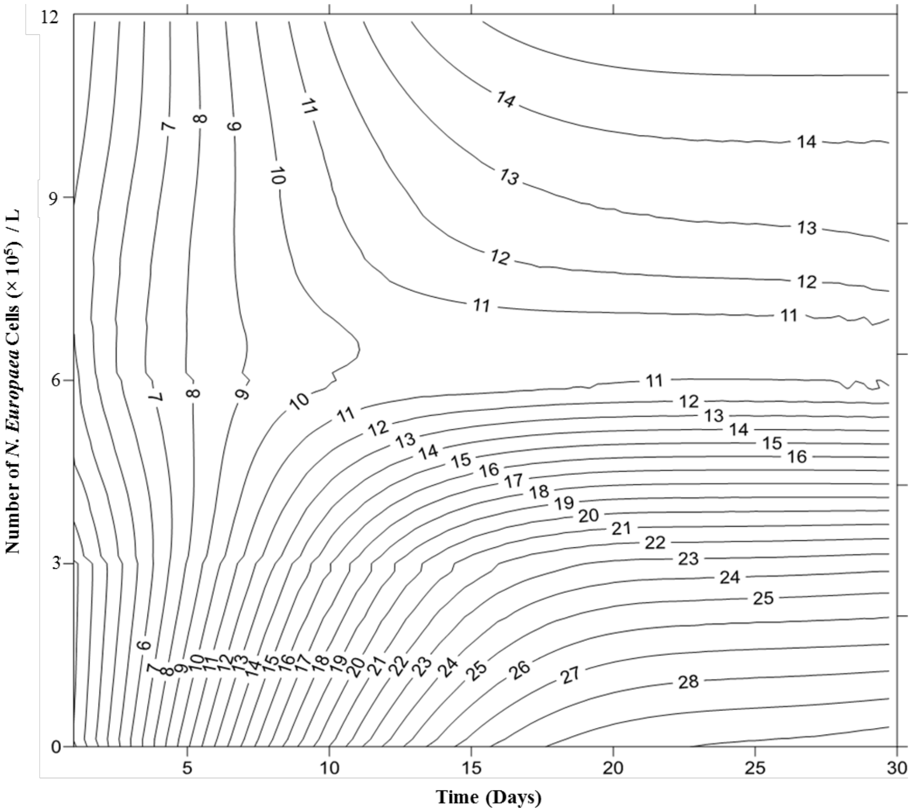

Figure 4.5. Percentage of Nitrogen Loss at Different *N. europaea* Bio-seed Concentrations and Durations

Figure 4.6 shows the nitrate:ammonium ratios at different *N. europaea* bio-seed concentrations and durations. This graph suggests that at a concentration of approximately 6×10^5 cells/L, the steady nitrate:ammonium ratio was 1:1.

Although the 1:1 ratio was also achieved with other bio-seed concentrations (e.g., 3×10^5 cells/L on the 7th day), it changed with time. However, at lower bio-seed concentration, a higher amount of nitrogen loss was noted (Figure 4.5).

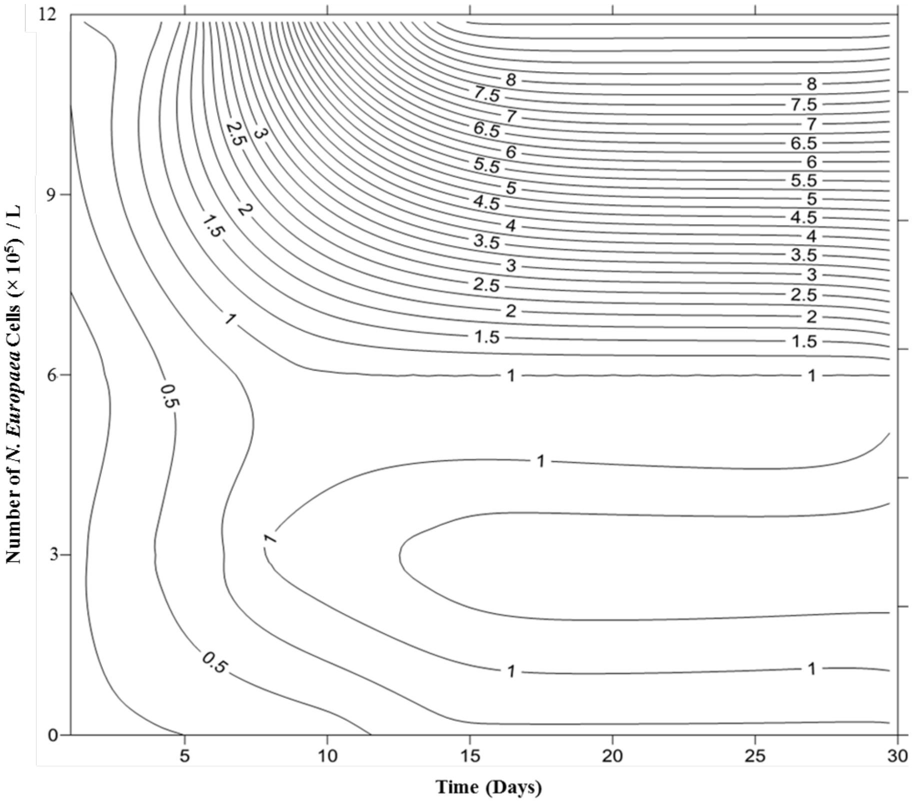

Figure 4.6. Nitrate:Ammonium ratio at Different *N. europaea* Bio-seed Concentrations and Durations

Furthermore, Figures 4.5 and 4.6 show that adding bio-seed at a concentration of 6×10^5 cells/L reduced the time required for stabilization from 15 days to less than ten days.

4.2.3.4. Application to the Ornamental Plant **Ipomoea nil**

To investigate the fertilization effect of stabilized urine mixed with 6×10^5 cells/L *N. europaea* bio-seed, we performed a simple experiment on the ornamental plant *Ipomoea nil*. Seeds of *I. nil* were cultivated in three cylinder-shaped pots with 7 cm base diameter and 9 cm height. Three-fourth of each pot was filled with cultivating soil provided by Hwabuns Company located in Seoul, Korea.

The characteristics of the cultivated soil are presented in Table 4.2. Stabilized urine (20 ml) mixed with *N. europaea* bio-seed was added to one pot, pure stabilized urine (20 ml) was added to the second pot, and the third pot was left intact.

Table 4.2. Physicochemical Characteristics of the Cultivating Soil Provided by Hwabuns Company

Material / Mineral	**Value**
Sand, (g kg^{-1})	893
Silt, (g kg^{-1})	99
Clay, (g kg^{-1})	51
pH	7.2
Ca, (cmol kg^{-1})	5.51
K, (cmol kg^{-1})	0.48
Mg, (cmol kg^{-1})	1.25
P_2O_5, (mg kg^{-1})	63.40
K_2O, (mg kg^{-1})	192.20

Irrigation was performed twice a day with 15 ml ordinary tap water derived from the water supply of Seoul Metropolitan City, and cultivation conditions were 27°C temperature and 65% humidity. Light condition was the same for all the pots.

Figure 4.7 depicts the growth of I. nil in all pots after 20 days, and Figure 4.8 shows the growth of I. nil for eight days in soil supplemented with the stabilized urine mixed with *N. europaea* bio-seed.

Figure 4.7. Comparing the Growth of Ipomoea nil after 20 Days in (a) Cultivated Soil Enhanced with 20 ml Stabilized Urine Mixed with 6×10^5 cells/L *N. europaea* Bio-seed (b) Cultivated Soil Enhanced with 20 ml Stabilized Urine and (c) Intact Cultivated Soil.

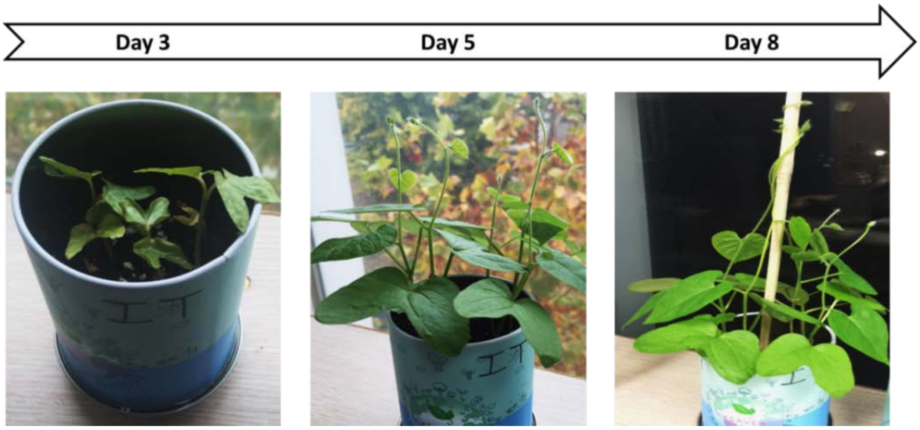

Figure 4.8 Growth process of *Ipomoea nil* for 8 Days in Cultivated Soil Enhanced with Stabilized Urine Mixed with 6×10^5 cells/L *N. europaea* Bio-seed

These results suggest that Ipomoea Nil showed the highest growth in the soil with stabilized urine supplemented with *N. europaea* bio-seed, in comparison with intact cultivating soil and soil mixed with stabilized pure urine.

4.3. Harvesting Nutrients from Source-Separated Urine Using Powdered Rice Straw

4.3.1. Background

As it is mentioned earlier, urine contains massive amounts of nutrients containing different compositions of phosphorus and nitrogen. Therefore, sending urine directly to the wastewater plants can cause nutrient overloading problems, and in the case of insufficient treatments, these nutrients can enter the natural water body and cause pollution (Hashemi and Han 2017c). To prevent this, as part of a trend in the development of resource-oriented sanitation practices, the determination of adequate on-site treatment methods for urine is essential to utilize it as fertilizer (Hashemi et al. 2016). However, because there is a significant amount of urine and it is in liquid form, handling it is difficult. Therefore, finding approaches for harvesting nutrients in a stable way is essential.

For this purpose, the addition of appropriate solid additives such as rice straw, peanut straw, maize cobs, and stover for harvesting nutrients from urine can be useful (Hashemi and Han 2017c). Among these additives, the utilization of rice straw is more common since it is a significant crop residue that farmers usually store for use as ruminant feed or as a soil conditioner in tropical areas, especially in Asia (Gunun et al. 2013, Han and Kim 2014).

Since rice straw is low in nutritive value with low levels of protein, various methods have been used to improve the nutritive value of rice straw, including physical, biological, and chemical treatments (Gunun et al. 2013, Sarnklong et al. 2010, Wanapat et al. 1985).

Previous studies have shown that a urea treatment can increase the nutritive value of rice straw (Hashemi and Han 2017c, Ørskov 1994, Ørskov 1998, Wanapat and Cherdthong 2009, Zaman and Owen 1990). Wanapat et al. (1985) reported that urea-treated rice straw could increase the overall intake and digestibility, which enhances the performance of ruminants and the growth of plants compared to untreated rice straw (Gunun et al. 2013, Wanapat et al. 1985).

However, fewer studies have focused on utilizing a controlled amount of rice straw for nutrient harvesting from human urine in ROS or RCS systems (Hashemi and Han 2017c). In such systems, because of urine storage processes, the urea in fresh urine will change into ammonia as mentioned by equation 4.1.

Therefore, it is essential to check the availability and efficiency of rice straw for harvesting nutrients from urine in such condition and to identify the types of harvested nutrients to find out if they can be utilized as fertilizer.

4.3.2. Materials and Methods

4.3.2.1. Collection of Raw Materials and Sample Preparation

Within 24 h, a total of 18 l of undiluted, fresh urine samples were gathered from a new empty tank at a men's public waterless urinal system installed in Building 35 at Seoul National University. Then, to attain conditions similar to stored urine in typical resource-oriented sanitation systems, the collected urine samples were stored in a Panasonic MIR cooled incubator (model MIR-254) with the temperature set to 15°C for 20 days [3,18]. These samples were labeled as 'Stale Urine' and immediately used in the "Nutrient Harvesting Experiment." Table 4.3 presents the initial characteristics of the stale urine samples. All chemical measurements were carried out following USEPA standards (USEPA 1979) using a HUMAS UV/Visible spectrometer (model HS-3300; Daejeon, Republic of Korea).

Table 4.3. Initial Characteristics of the Collected Urine

Composition	PO_4^{3-}	NH_4^+	Mg^{2+}	Ca^{2+}	pH
Concentration (mmol/l)	43.8	336.6	41.0	22.9	9.79

Powdered rice straw was gathered from GnV Company (Gunpo City, Gyeonggi Province, Republic of Korea). The mean surface area of the rice straw particles was measured with a KES 2006 video optical microscope using the ITPro software Version 3.03, both developed by Sometech Inc. (Seoul, Republic of Korea), to be around 25 μm^2. For investigating the characteristics of the rice straw samples, the contents of Mg and Ca in the powdered rice straw sample were analyzed by atomic absorption spectrophotometry (AAS) after wet digestion using an auto-sampler system apparatus, model AA-7000G (Shimadzu Company, Kyoto, Japan) (Hashemi and Han 2017c). The amount of P was measured by colorimetry following the USEPA standard (Hashemi and Han 2017c). Table 4.4 presents the measured characteristics of the powdered rice straw samples.

Table 4.4. Characteristics of the Powdered Rice Straw

Minerals	**Mg**	**P**	**Ca**
Concentration (g/kg)	1.2	1.0	3.9

To reduce the effect of evaporation and prevent the introduction of any external particles into the samples, 18 1-l Ziploc plastic bags were provided. Among them, 15 bags were filled with different amounts of rice straw: 100 mg (three bags), 200 mg (three bags), 300 mg (three bags), 400 mg (three bags), and 500 mg (three bags), and three were left empty. Then, all bags were filled with 1 l of stale urine and tightly sealed.

4.3.2.2. Nutrient Harvesting Experiment

To ensure that urine and rice straw particles are in complete contact and interact, all 18 bags were shaken with an orbital motion speed of 180 rpm using Green Shaker II (model VS-203P; TecDev, Belmont-sur-Yverdon, Le Villaret Switzerland) for 12 h.

After shaking, all bags were stored in the incubator with the temperature set to 15°C. Every three days, the concentrations of the total ammonia, total phosphate, magnesium, and calcium were measured for all samples. Moreover, Aquaread Aquaprobe (model AP-2000) was used for the pH measurement. All measurements of bags with a similar amount of rice straw were triplicated, and an arithmetic mean was taken as the final result. The concentrations of all elements did not change significantly after 30 days, so the experiment was ended at this point.

4.3.2.3. Identifying Harvested Nutrients

To identify the harvested nutrients, after day 30, 50 mg of fertilized rice straw powder was kept for 15 days inside a Test Mark Industries desiccator (model CA-1336) to be slowly dried. The dried samples were examined with the optical microscope to observe the formed nutrient scales.

For verifying the identification of the nutrients, powders were characterized using X-ray crystallography by a MiniFlex 600 benchtop X-Ray diffractometer (XRD) (Rigaku Corporation, Akishima-shi, Tokyo, Japan). The experiment was carried out using X-ray radiation with a wavelength of 0.1541838 nm, and verification was performed using the X-ray line diagram references available within the integrated X-ray powder diffraction software (PDXL version 2.6.1.2, Rigaku Corporation).

4.3.3. Results and Discussion

4.3.3.1. Interaction between Urea and Rice Straw Powder

Figure 4.9 presents the trends of the different ions in the samples with different amounts of powdered rice straw. The numbers in the body of the graphs are the concentrations of specific ions in units of millimoles per liter.

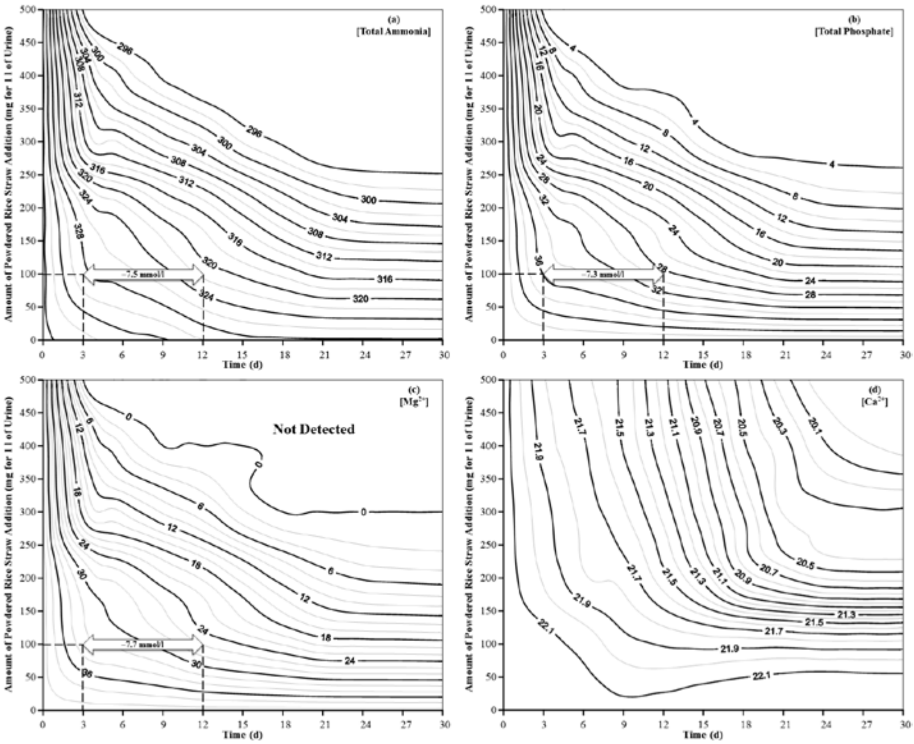

Figure 4.9. Effect of Different Amounts of Powdered Rice Straw on the Nutrients over Time of the (a) Total Ammonia, (b) Total Phosphate, (c) Magnesium Ions, and (d) Calcium Ions. The Numbers in the Body of the Contour Graphs are the Concentrations of the Ions in Units of mmol/l.

NH_4^+, Mg^{2+}, and PO_4^{3-} showed similar reduction trends, while Ca^{2+} showed no notable reduction. In comparison with other samples, the sample without the addition of rice straw powder showed less ion reduction and samples with more rice straw showed a more significant reduction. Also,

Mg^{2+} seemed to dominate the harvesting process; after it becomes undetectable (less than 0.001 mg/l = 0.00004 mmol/l), no more significant reductions were observed for NH_4^+ and PO_4^{3-}.

In a constant addition of powdered rice straw, when the amounts of ion reduction were compared, similar amounts of each ion were found to have been reduced. For example, when 100 mg powdered rice straw for 1 liter of urine is added; the same amounts of precipitation occurred from day 3 to day 12: about 7.5 mmol/l of each ion. No notable trend was observed for changes in the pH of the samples. However, it always had a value of 9.5–10.

4.3.3.2. Efficiency of Harvesting Nutrients

Figure 4.10 presents the percent reduction of different ions in the samples with different amounts of rice straw powder added.

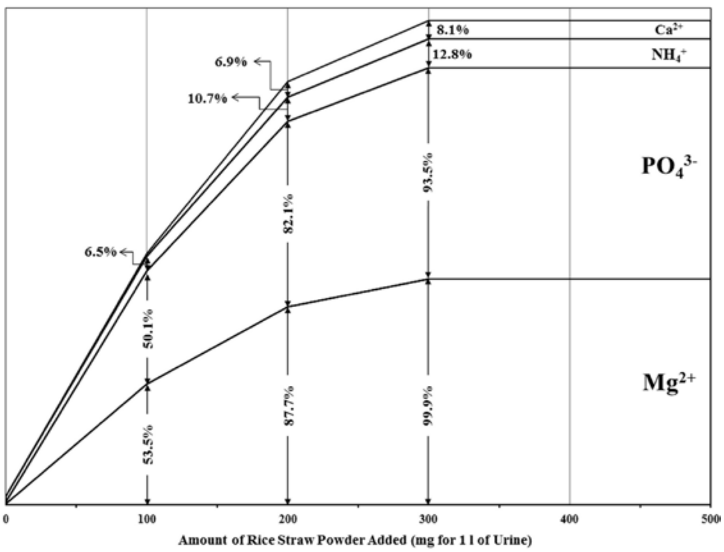

Figure 4.10. Percent Reduction of Different Ions in Samples with Different Amounts of Rice Straw Powder Added.

As presented, the percentage of ion reduction is relatively high for the two compounds of PO_4^{3-} and Mg^{2+}. This may be explained by the characteristics of rice straw. The contents of Mg and P in the rice straw samples are three times lower than the content of Ca, which allows rice straw to adsorb relatively more P and Mg compounds in a better manner.

Furthermore, the addition of 300 mg of rice straw powder reduces nearly all of Mg^{2+}. The addition of more additives cannot cause more nutrient harvesting after such a reduction in Mg^{2+}. This occurs when about 87% of the ammonia and 6.5% of the phosphate remain in the urine. This may indicate that improving the efficiency of nutrient harvesting is possible by the addition of magnesium ions and phosphate to balance their molarity with ammonia.

4.3.3.3. Identifying the Harvested Nutrients

As noted above, the reduction processes of NH_4^+, Mg^{2+}, and PO_4^{3-} are very similar, and the same molarity for each ion was reduced for every time interval. This led to the hypothesis that the majority of harvested nutrients could be struvite.

To confirm this hypothesis, the salts precipitated on the slowly dried powdered rice straw were examined under a microscope. Figure 4.11 shows a microscope image. In this image, the salts showed a porphyritic and compact morphology, which is consistent with struvite (Hashemi et al. 2015a).

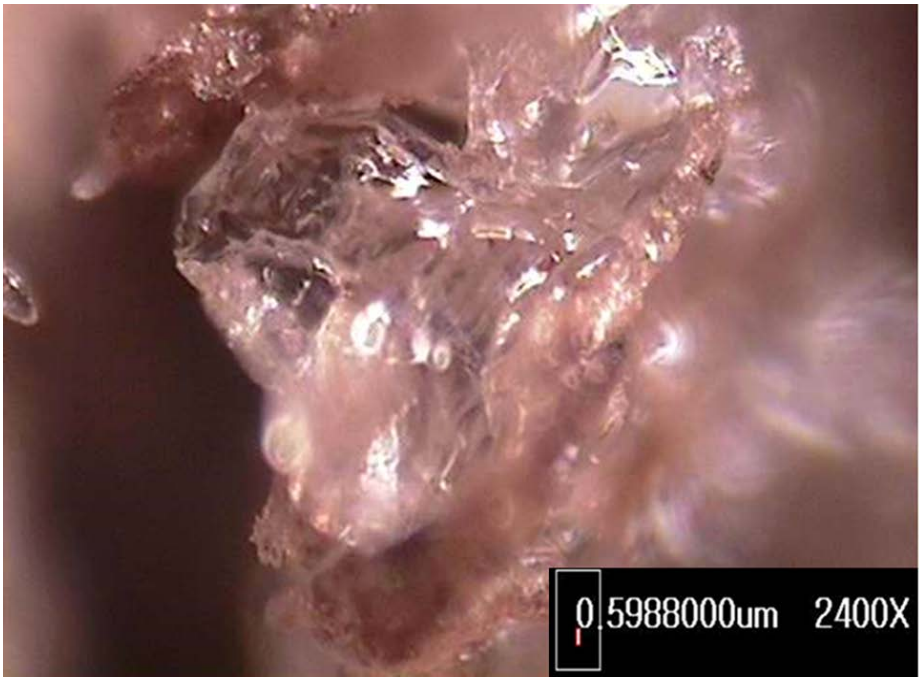

Figure 4.11. Microscope Image of the Scale Formed on the Powdered Rice Straw.

Figure 4.12 presents the results of the XRD analysis, which verify the formation of crystalline struvite by the location of the peaks, which correspond to the reference X-ray lines for struvite based on the Joint Committee for Powder Diffraction Standards (JCPDS) Reference Card Number 1-077-2303, available in the analysis software.

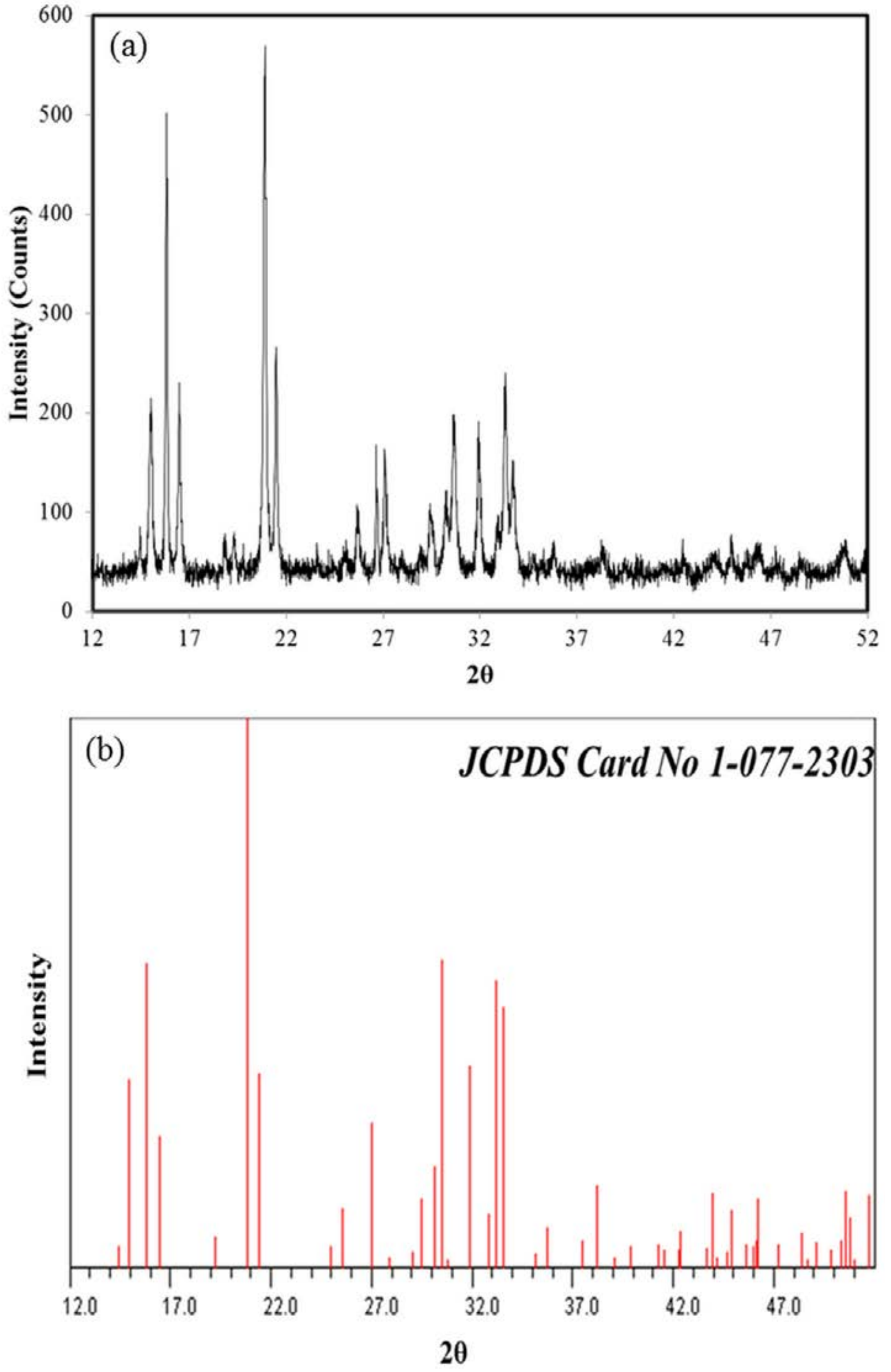

Figure 4.12. (a) XRD Analysis of the Samples and (b) Reference X-ray Line Diagram for Struvite.

4.4. Conclusions

Investigation of the chemical changes in nitrogen compounds in pure urine showed that there is extensive nitrogen loss, implying a loss of nutrients and production of odor. Moreover, the time required for the stabilization of nitrogen compounds is approximately 15 days. Therefore, open defecation or direct urination over the plants is not an appropriate practice, and urine should be stored first to be stabilized.

Addition of *N. europaea* bio-seed can influence the nitrogen composition by way of nitrification, which leads to reductions in nitrogen loss and stabilization time. However, adding excess bio-seed leads to higher production of nitrate, which can cause soil pollution. We identified the optimum dosage range of bio-seed of 6×10^5 *N. europaea* cells/mL, which ensures the best fertilization characteristics of urine, according to the EC standards. This bio-seed dosage results in not only a nitrate:ammonium ratio of about 1:1 and higher efficiency of cultivating ornamental plants such as *I. nil* but also the lowest nitrogen loss and least stabilization time; this prevents over-fertilization and eliminates the need for dilution or dewatering, thereby lowering water and energy consumption. Another advantage of using this optimum concentration of bio-seed is that further application of inorganic chemical additives is not required.

Nutrient harvesting by powdered rice straw was studied by examining the reduction processes of NH_4^+, PO_4^{3-}, Mg^{2+}, and Ca^{2+}. NH_4^+, Mg^{2+}, and PO_4^{3-} showed similar molarity reduction trends. Even though almost all of the magnesium and phosphate were reduced by the additives, less than 20% of the ammonia was harvested owing to the lower amounts of magnesium ions and phosphate compared to ammonia.

The efficiency of nutrient harvesting might be improved by balancing the molarity of the phosphate and magnesium in the urine samples. This can be done by adding safe soluble salts such as magnesium acetate or dipotassium phosphate. Microscopy images and an XRD analysis confirmed that the majority of the harvested nutrients was struvite. Therefore, it was found that powdered rice straw is efficient at harvesting nutrients inside urine.

This process is suitable for RCS systems, especially in the rural areas of developing countries, which are based on treating and utilizing source-separated pure urine. As a suggested source-separation urine-treatment process, the addition of powdered rice straw and modification of the molarity of the nutrients to improve the process of nutrient harvesting can be useful. This is because the additives can be utilized as solid fertilizer after the treatment, and the remaining urine can be used for irrigation purposes or sent to wastewater treatment plants.

5. Feces Management

5.1. Introduction

As mentioned in previous chapters, the sanitation systems commonly in use have several serious challenges, including high water and energy consumption and nutrient overloading to wastewater treatment plants (Han and Hashemi 2017).

New approaches in the design of the sanitation systems such as the RCS are required to overcome these challenges (Han and Hashemi 2017, Han et al. 2016, Kim et al. 2016). Partially similar to the Onsite Wastewater Differentiable Treatment Systems (OWDTS), RCS is based on the source separation of urine and feces, consumes no water or significantly less water than conventional systems, and utilizes human sanitary wastes as fertilizers or soil conditioners.

However, RCS has some of its challenges, especially in feces handling and utilization. High feces volume and slow degradation process cause difficulties in storage. For utilizing the feces as a fertilizer, monitoring its nutrient composition, e.g., its nitrogen components, is essential (Hashemi and Han 2017b).

Figure 5.1 presents the characteristics of pure fresh feces in a simple way. It typically contains 75% water, 14% organic compounds (organic carbons) and 1.2% other compounds including N, P, and K compounds.

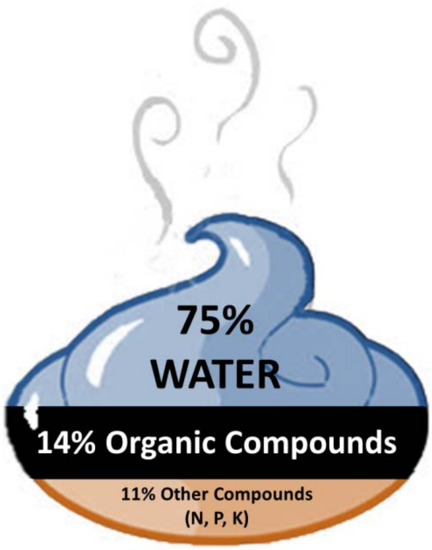

Figure 5.1. Simplified Schematic of Characteristics of Pure Fresh Feces

Same as for the case of urine, handling and utilizing human feces are closely related so that if the waste is going to be utilized as a fertilizer, then it should be handled appropriately.

Plants absorb nitrogen from the soil in the form of nitrate and ammonium. According to European Commission (EC) regulations, the co-occurrence of these two compounds in the nitrogen composition of fertilizer is an important indicator of its efficiency (European Commission 2003, Hashemi et al. 2016, Xu et al. 2012).

Although the use of microorganisms to accelerate the degradation rate is common, for more sustainable and efficient waste management, such methods should also address the utilization of the waste as fertilizer. For these purposes, the use of nitrifying microorganisms would be advantageous (Wagner and Loy 2002).

As mentioned earlier, nitrification is the process of converting ammonium (NH_4^+) into nitrite (NO_2^-) and subsequently into nitrate (NO_3^-), which is commonly carried out by two separate groups of microorganisms.

However, the oxidation of nitrite involves a lower free-energy change, which means that the oxidation of ammonium is the critical step from which ammonium-oxidizing microorganisms, such as *N. europaea*, obtain energy (Texier et al. 2012). Furthermore, according to Laanbroek and Gerards (1993), *N. europaea* has lower stamina as an ammonium oxidizing bacteria compared with *Nitrobacter winogradskyi (N. winogradskyi)* as a nitrite oxidizing microorganism.

Furthermore, the standards of the European Commission (EC) prescribe a ratio of 1:1 for NH_4^+ and NO_3^- in nitrogen fertilizer. Also, the pH must be between 5.0 and 7.5 to be classified as a standard fertilizer (European Commission 2003). Thus, it would probably be useful to control the amount of *N. europaea* bio-seeds added, along with the addition of *N. winogradskyi*, to the treatment process with nitrifying microorganisms. In this way, favorable growing conditions could be ensured to obtain treated feces of which the composition is close to that of standard fertilizer.

Although previous studies have indicated that *N. europaea* could utilize the insufficient amount of halogenated organic compounds (Hommes et al. 2003, Krümmel and Harms 1982), both the abovementioned nitrifying microorganisms are obligate chemolithoautotrophic bacteria that mainly utilize CO_2 instead of organic carbon (Wagner and Loy 2002).

About the enhancement of the degradation of source-separated feces, it is thus essential to investigate the effect of this treatment procedure on the growth of heterotrophic microorganisms existing in the feces. Therefore, as stored source-separated human excreta in RCS is rich in nitrogen compounds such as ammonium, as well as inorganic compounds, utilization of nitrifying microorganisms might be useful for degrading the source-separated feces and obtaining the benefit of its nitrification function for modifying its nitrogen components (Hashemi and Han 2018, Texier et al. 2012, Wagner and Loy 2002, Zavala et al. 2005).

To the best of our knowledge, very few studies have focused on the effect of nitrifying microorganisms bio-seed addition on feces volume reduction as well as improving its fertility. Furthermore, the treatment process should be hygienic to prevent any public health risk (Hashemi et al. 2018). Accordingly, in this chapter, we investigate the effect of adding different amounts of *N. europaea* bio-seed on the degradation rate, the NO_3^- to NH_4^+ ratio, and the growth of heterotrophic microorganisms, as well as pathogens, existing in source-separated feces. Also, we determine the optimum amount of bio-seed addition for maximum degradation, and to render the treated feces suitable for use as fertilizer.

5.2. Materials and Methods

5.2.1. Sample Preparation

Fresh samples (collected within 24 hours using a 20 L sterile sampling bag) of raw source-separated feces were obtained from the feces storage tank of an ROS system, as described by (Han et al. 2016). The construction and operation of the ROS system were carried out by the GnV Company (Gunpo City, Gyeonggi Province, Republic of Korea). This system is located in a public park near the West Suwon Lake Prugio Residential Complex Phase 1 at Gunpo City, Gyeonggi Province, Republic of Korea (37°18′00″N, 126°47′11″E). The same company provided two stabilized bio-seed solutions, one of which contained 6×10^6 *N. europaea* cells per 100 mL, and the other 8×10^5 *N. winogradskyi* cells per 100 mL. Both bio-seed solutions include various microbial growth promoters including amino acids and vitamins.

Twenty-one sets of samples were prepared in 1 L beakers as a batch system, with each set containing three samples (total 63 samples), intended as analytical repeats of the experiment. Each sample included 300 g feces, representing the usual defecation amount of a single event (Shier et al. 2016). One set of samples was left untreated as the control, whereas different amounts of bio-seed were added to the other sets of samples. By diluting the bio-seed solutions, 1,000 to 20,000 cells of *N. europaea* bio-seed were added at 1,000 cell increments to 1 g feces. Also, a specific fixed amount of 10,000 *N. Winogradskyi* cells to 1 g feces were added to the samples of each set, except the control set, ensuring that all the samples had the same amount of this bio-seed. The reason for selecting this range in concentrations is that it facilitates investigating the nitrification process as a function of the amount of *N. europaea* bio-seed being both higher and lower than the amount of *N. winogradskyi* bio-seed.

Using laboratory mixers (Cole-Parmer, USA, model EW-04555-00), the samples were mixed well at a speed of 45 rpm. After mixing, the samples became homogeneous, soft, and creamy. During the experiment, the samples were turned over twice daily using the mixers at a speed of 45 rpm for 10 minutes.

To avoid any bacterial interactions, all beakers and mixing blades were first disinfected using a 70 % ethanol solution provided by Samchun Chemical (Republic of Korea) and subsequently placed in a sterilizing oven (Shimwon Ultraviolet Ray, Model SW305H, Republic of Korea), using four 15 W UV lamps for 90 minutes. All the sets of samples were placed in a similar condition during the experiment. The initial temperature of the samples and the experimental environment were maintained at 25 °C, which is the optimum temperature at which the nitrifying bio-seeds are active (Grady Jr et al. 2011).

According to Zavala and Funamizu (2005), low moisture content (< 64 %) ensures the aerobic degradation of feces, and therefore, the moisture content was maintained as low as possible by keeping the batch system open for evaporation and frequently turning over the samples. The system was covered with net sheets to prevent insects or other objects from entering the system.

5.2.2. Characteristics Analysis

Using samples from each set, the amounts of total solids (TS), volatile solids (VS), and initial water content were determined gravimetrically at intervals of three days using Method No. 1684 of the US Environmental Protection Agency (Hashemi and Han 2018). The total organic carbon (TOC) was measured according to the US Department of Agriculture (USDA) standards, as described by Sikora and Stott (1996), and using ELTRA CHS-580A Carbon/Hydrogen/Sulfur Analyzers (ELTRA GmbH, Germany).

The percentages of TS, VS, and TOC at each measuring interval were calculated by dividing the measured value by the initial amount and taking the difference between this value and 100 as the progress of degradation. The Lee Valley Soil pH Meter, Model AB927 (Lee Valley Tools Ltd., Ogdensburg, New York, USA) was used for pH measurement.

Using 1 g samples from each set, the liquid extracts of feces were prepared with 100 ml distilled water. To avoid any unwanted bacterial interaction, the water samples were placed in the abovementioned UV sterilizing oven for 12 hours before conducting the experiment. The concentrations of total nitrogen (TN), total ammonia (NH_3), ammonium (NH_4^+), and nitrate (NO_3^-) in these extracts were determined using the HUMAS UV/Visible spectrometer, Model HS-3300 (HUMAS, Korea). The measurements followed the Standard Methods for the Examination of Water and Wastewater of the American Public Health Association (APHA/AWWA/WEF 2012). At each measurement interval, the percentage of each nitrogen compound was calculated by dividing the measured value by TN, after which the ratio of NO_3^- to NH_4^+ and was calculated.

These extracts were also used for the enumeration of the heterotrophic microorganisms as well as measuring *Escherichia coli* (*E. coli*) and total coliforms. For this purpose, 3M™ Petrifilm™ Count Plates (3M, USA) were used and subsequently incubated. They were then interpreted following ISO 6222 (ISO, 1999). The detection limit for this method was $\log_{10}$ (CFU/1 g feces) = 2.

Using the three samples in each set, all measurements were done in triplicate, and an arithmetic mean was taken as the final result. Each dependent parameter is strongly related to two independent ones, comprising the time and the initial addition of *N. europaea* bio-seed. Therefore, to present such a bivariate model, the results were plotted as three-dimensional contour diagrams through local polynomial regression.

Table 5.1 presents the initial characteristics and nitrogen composition of the untreated feces sample. The experiments lasted for 30 days, but the condition of all the samples stabilized after approximately 20 days, with no significant changes being detected thereafter.

Table 5.1. Initial Characteristics of Collected Feces

Parameter	**Unit**	**Concentration**
Water Content	%	63.8
Total Solid (TS)	mg per g	286
Volatile Solid (VS)		243
Total Organic Carbon (TOC)		147
Total Nitrogen (TN)	mg N per g	16.8
Total Ammonia		12.4
Ammonium (NH_4^+)		11.9
Nitrate (NO_3^-)		Not Detected
pH	-	7.8
Heterotrophs	$\log_{10}$ CFU per g Feces	7.2

5.3. Results and Discussion

5.3.1. Feces Degradation Process and Optimization

Figures 5.2 to 5.4 show the degradation process of the samples versus time through contour diagrams. The samples contain 10,000 *N. Winogradskyi* cells for 1 g feces, as well as various amounts of *N. Europaea* bio-seed. A similar degradation process was observed for TS, VS, and TOC. The degradation is rapid at the beginning, but the degradation rate decreases slightly over time.

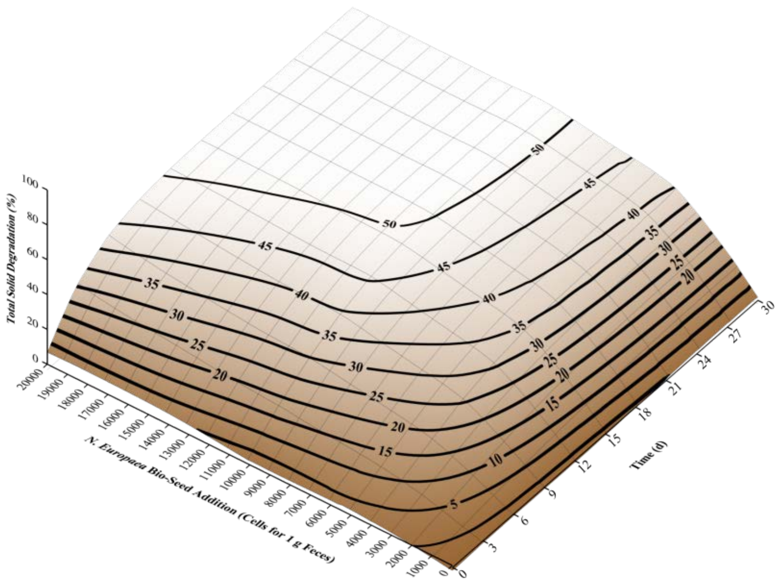

Figure 5.2. Degradation of Total Solids in the Experimental Samples

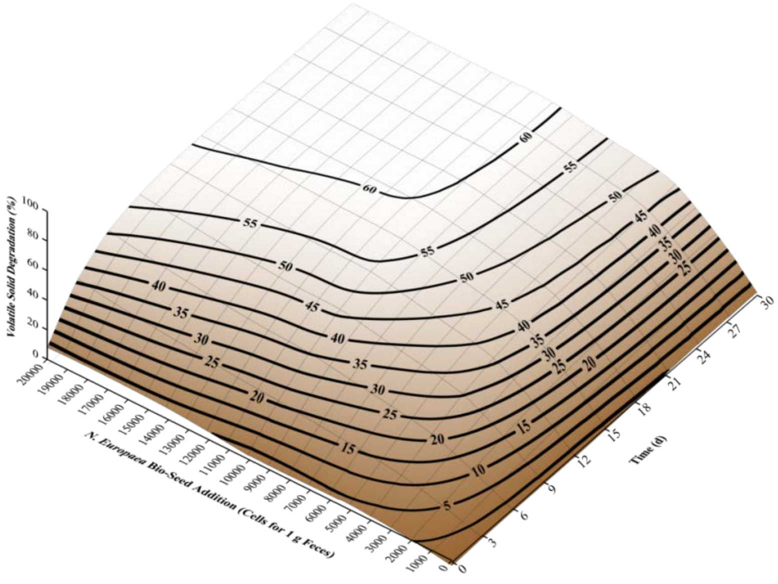

Figure 5.3. Degradation of Volatile Solids in the Experimental Samples

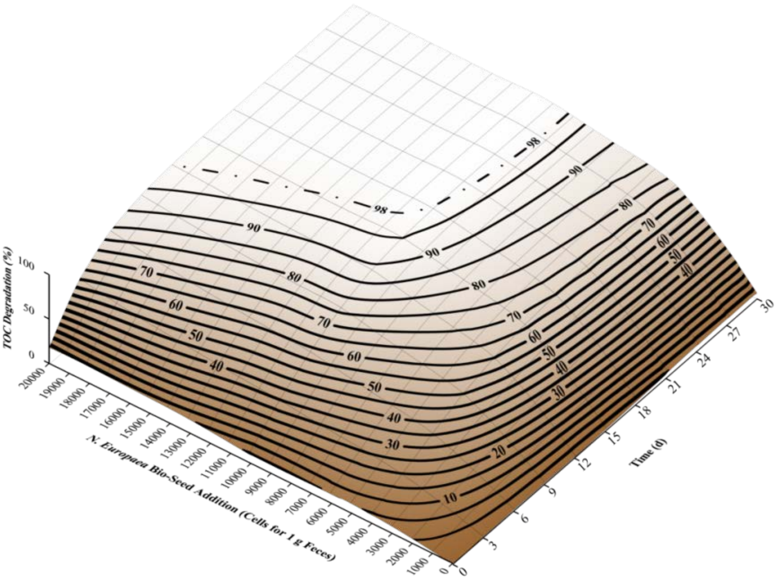

Figure 5.4. Degradation of Total Organic Carbon in the Experimental Samples

Approximately 22–25 % degradation was observed for both TS and VS as a function of a specific *N. Europaea* bio-seed concentration (e.g., 10,000 cells for 1 g feces) over a specific period (e.g., days three to nine).

However, the rate of degradation for TOC was twice as fast (approximately 41 % in six days). Furthermore, limits of 50 % and 60 % were observed in the TS and VS degradation processes, respectively. This could be attributed to the maximum digestion of TOC, observed to be approximately 98 %, after which the TS and VS degradation processes stopped. Consequently, the digestion rate of TOC was not 100 %, which could be attributed to the existence of abundant autotrophic microorganisms.

It was observed that the initial addition of 7,000 cells of bio-seed for 1 g feces could facilitate about 90 % degradation of the TOC after 30 days. The next increment can reduce this time down to about 18 days.

Although the addition of more bio-seed reduces the required time for complete TOC digestion, the nitrogen composition (the ratio of NO_3^- to NH_4^+) and the pH of the feces must be monitored so that the waste can be subsequently used as fertilizer.

5.3.2. Optimizing the Fertility of Feces

Figures 5.5 and 5.6 present the changes in the ratio of NO_3^- to NH_4^+ and the pH, respectively, for samples that contain 10,000 *N. winogradskyi* cells for 1 g feces, as well as various added amounts of *N. europaea* bio-seed versus time. In the samples with added bio-seed, the ratio of NO_3^- to NH_4^+ increased.

The increment of the ratio can be explained by considering the nitrification process, in which the nitrifying bio-seeds turn NH_4^+ to NO_3^-, where NH_4^+ can be oxidized by *N. europaea* bio-seed into NO_2^-, which in turn can be oxidized into NO_3^- by *N. winogradskyi (Hashemi and Han 2017b, Hashemi and Han 2018, Hashemi et al. 2016).*

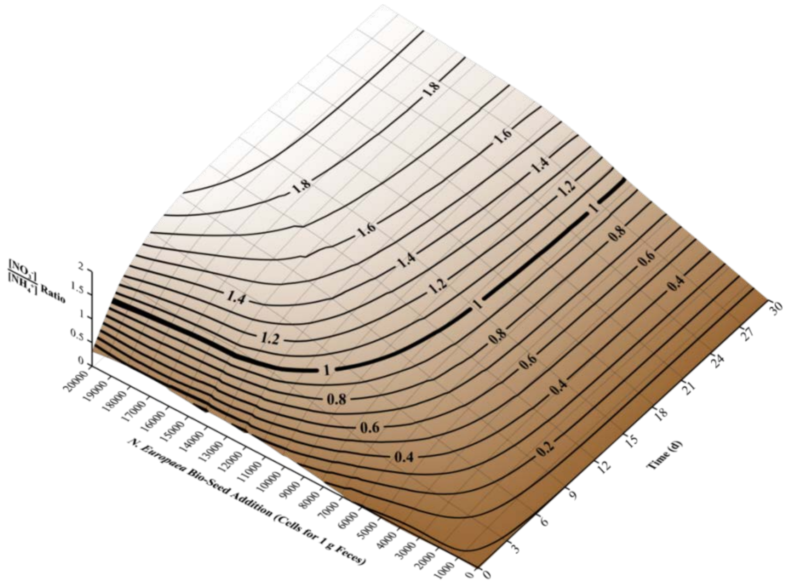

Figure 5.5. Variation of Nitrate to Ammonium Ratio in the Experimental Samples

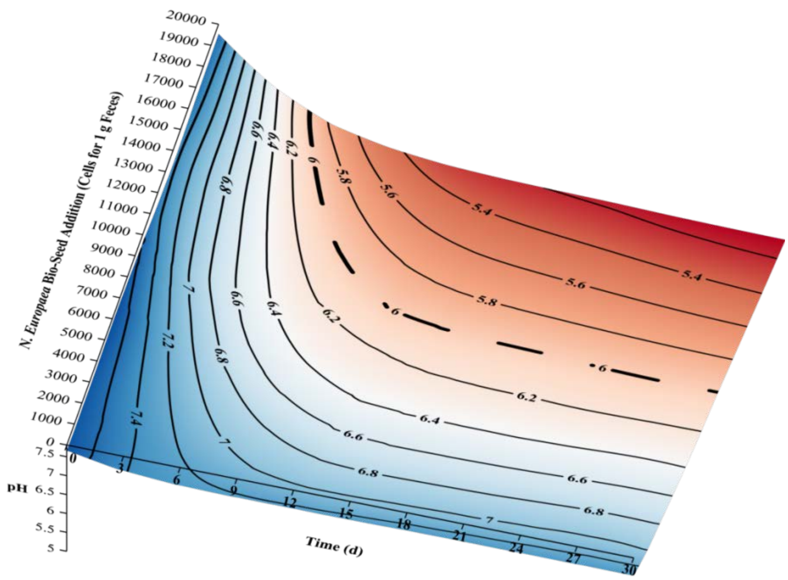

Figure 5.6. Variation of pH in the Experimental Samples

According to Figure 5.5, by increasing the added amounts of *N. europaea* bio-seed, the speed of nitrate production was increased, especially in the first six days of the experiment. This can probably be attributed to the increased production of nitrite by *N. europaea*, which was subsequently oxidized by *N. winogradskyi*. When the *N. europaea* bio-seed addition was lower than the *N. winogradskyi* bio-seed addition, the nitrate production was weak, although the pH level was favorable for the nitrification process. This is probably caused by the lower steady state of *N. europaea* compared with *N. winogradskyi (Laanbroek and Gerards 1993)*.

Also, as suggested by Figure 5.5, the nitrification process was rapid in the beginning but slowed down with time. This can probably be explained using the results obtained from pH monitoring, which are shown in Figure 5.6. In the case of higher nitrate production, the pH level dropped below 6.5, corresponding to conditions that no longer favored survival of the nitrifying bacteria, and thus the nitrification process could not proceed (Grady Jr et al. 2011).

However, with a concentration of 7000–8000 *N. Europaea* bio-seed cells to 1 g feces, the ratio of NO_3^- to NH_4^+ was maintained at approximately one after 12–21 days. This composition meets the criteria for fertilizer in respect of both the NO_3^- to NH_4^+ ratio and pH level (Hashemi and Han 2018).

5.3.3. Effect of Addition of Nitrifying Bacteria on Heterotrophic Microorganisms

As mentioned before, both *N. europaea* and *N. winogradskyi* are known to be autotrophic, and their heterotrophic growth is therefore quite limited. Consequently, in the case of a high rate of digestion of TOC, as was observed in this study, the main digestion procedure should occur by other heterotrophic microorganisms, such as the facultative microorganisms that exist naturally in source-separated feces. As a consequence of using this procedure, the effect of adding bio-seed on the growth and activities of heterotrophic microorganisms was examined.

Figure 5.7 presents the results of the enumeration of the heterotrophic microorganisms in the untreated feces sample, as well as the samples that contain 10,000 *N. winogradskyi* cells for 1 g feces together with the different amounts of *N. europaea* bio-seeds, as a function of each measurement time interval, and the initial addition of bio-seed.

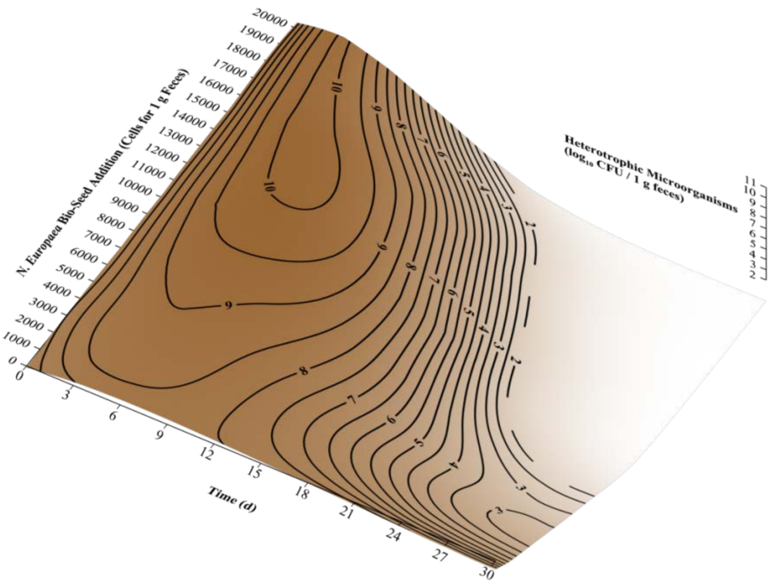

Figure 5.7. Variation of Amount of Heterotrophic Microorganisms in the Experimental Samples

The results show that for the untreated feces, the number of heterotrophic microorganisms increases after a short time, and subsequently remains constant after a slight reduction. It was observed that the addition of nitrifying bacteria significantly increases the number of heterotrophic microorganism in the first twelve days, which subsequently declines to a certain amount before becoming constant, for *N. Europaea* bio-seed addition of fewer than 7,000 cells to 1 g feces. In the case of higher bio-seed additions, no heterotrophic microorganisms are detected after a specific time.

5.3.4. Fate of *E. coli* and Total Coliforms in Intact Feces

Figure 5.8 presents the changes in the numbers of *E. coli* and total coliforms in intact feces. For a short period initially, the microorganism population increased. However, after this initial growth phase, the microbial population eventually decreased.

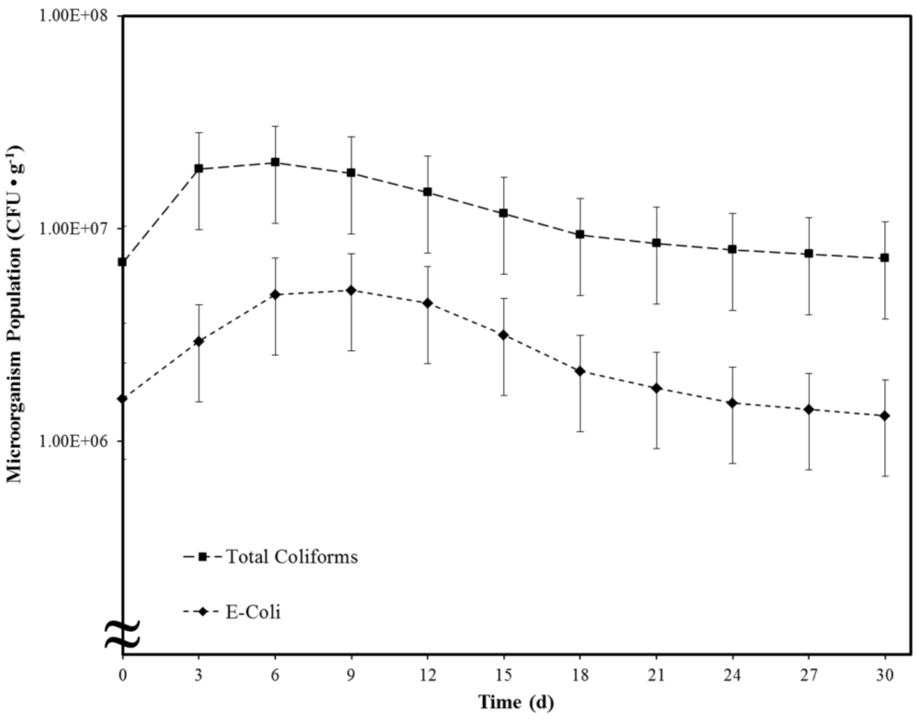

Figure 5.8. Changes in the Microorganism Population in 1 g of Intact Feces with Time

After 21 days, there was no significant change in the microbial population, implying that the rates of microbial growth and death may have become equal.

5.3.5. Effect of Adding Nitrifying Microorganisms on Fate of *E. coli* and Total Coliforms

Figure 5.9 presents the changes in the population of *E. coli* and total coliforms by adding different amounts of *N. europaea* bio-seed along with a constant amount of *N. winogradskyi* bio-seed.

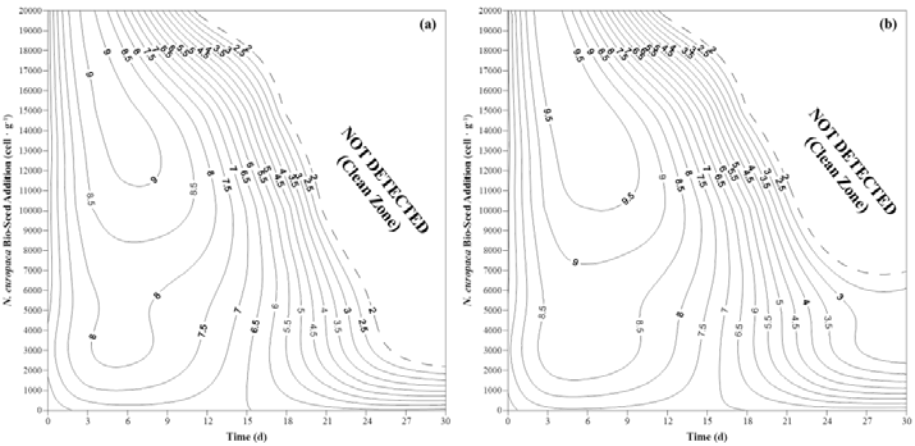

Figure 5.9. Changes in (a) Total *E. coli* Population and (b) Total Coliform Population in Experimental Samples with Different Amounts of Nitrifying Bio-Seeds in 1 g of feces. Numbers in Contours Represent log10 CFU • g^{-1}

The general trend observed after adding varying amounts of nitrifying microorganisms on *E. coli* and total coliforms was the same. The addition of bio-seeds initially increased the microbial population, which decreased over time. The minimum amounts of *N. europaea* bio-seed required to achieve the clean zone were 3000 and 7000 cells per 1 g feces, respectively, for *E. coli* and total coliforms.

For both *E. coli* and total coliforms, the highest microbial population was observed when the amount of *N. europaea* bio-seed added was higher than the constant amount of *N. winogradskyi* bio-seed (10,000 cells to 1 g feces).

5.3.6. Comparison of Time Required for Removing *E. coli* and Total Coliforms

Figure 5.10 presents the time required for the complete removal of pathogens by adding different amounts of nitrifying microorganisms. In the case of low addition of nitrifying microorganisms of 0 – 3,000 cells and 0 – 7000 cells to 1 g feces, there is no complete pathogen removal for *E. coli* and total coliforms, respectively. Consistently, adding a higher amount of nitrifying bio-seeds reduced the time required for complete pathogen removal.

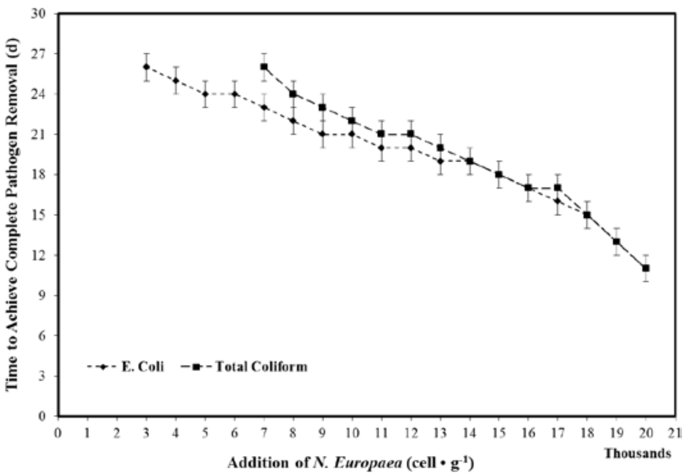

Figure 5.10. Time to Achieve Complete Pathogen Removal in Experimental Samples with Different Amounts of Nitrifying Bio-Seeds per 1 g of Feces

As mentioned previously, the minimum amount of bio-seeds required for complete removal of *E. coli* is lesser than that for total coliforms. However, as the amount of nitrifying bio-seeds added increases, the time required to achieve a clean zone for total coliforms approaches that of *E. coli*. For instance, in the case of adding 20,000 cells per 1 g feces, the time required to achieve clean zones for both *E. coli* and total coliforms are the same at 11 days.

5.3.7. Discussions

It is known that the presence of ammonia limits the growth of some facultative microorganisms including pathogens (Leejeerajumnean et al. 2000). Therefore, the increase in the number heterotrophic microorganisms along with bio-seed addition in the first twelve days could be attributed to the reduction of ammonia as a result of nitrification.

On the other hand, with the rapid and higher production rate of nitrate, especially with the addition of higher amounts of bio-seeds, the pH drops rapidly and significantly which can reduce the number of habitat microorganisms. Along with pH, the availability of organic compounds plays a vital role in the vitality of microorganisms. After high-level degradation of TOC, especially in the cases of higher amounts of bio-seed addition, the number of heterotrophic microorganisms declines significantly from the second week, while no heterotrophic microorganisms, including pathogens, were detected from the third week.

Finally, as it is mentioned earlier, the bio-seed solutions include various microbial growth promoters including amino acids and vitamins. Existence of these nutrients can play an essential role in the efficiency of applying nitrifyers so that the can competitively process the nitrification procedure along with the existence of other heterotrophs and high amount of organic compounds.

5.4. Conclusions

In this study, we investigated the effect of adding different amounts of *N. europaea* bio-seed, along with a fixed and certain additional amount of *N. winogradskyi* bio-seed, on the degradation process and the NH_4^+ to NO_3^- ratios of source-separated feces.

It became clear that the addition of nitrifying microorganisms modifies the existence and concentrations of nitrogen compounds such as NH_4^+ and NO_3^-, which could increase the number of heterotrophic microorganisms and enhance feces degradation. Afterward, the number of heterotrophic microorganisms reduces due to unfavorable pH condition as well as limited amount of organic matters. For the degraded feces to meet the criteria for standard fertilizer, the addition of *N. europaea* bio-seed must be controlled to maintain the ratio of nitrate to ammonium at 1:1.

Our results show that additional amounts of 7,000–8,000 *N. europaea* cells to 1 g feces, along with 10,000 *N. winogradskyi* cells per 1 g feces, could be considered optimal, as such treatment resulted in over 90% degradation of TOC within 21 days. Also, a sustainable 1:1 ratio of nitrate to ammonium and pH of between 6.2–6.4 was achieved, meeting the criteria for standard fertilizer.

We also investigated the fate of *E. coli* and total coliforms in intact feces. Results showed that the reduction rate of microorganisms in these samples is slow. This poses potential health challenges in the case of lack of treatment or improper sanitation practices such as open defecation. It was found that the addition of nitrifying microorganisms is useful for reducing pathogens in feces.

Such an approaches could be useful in various practices of RCS systems, as well as ROS systems which are unable to perform proper composting or other appropriate treatment processes for feces, especially in low to middle-income countries. An innovative approach for designing fecal treatment reactors is thus an essential future direction and deserves to be investigated in a separate research.

6. Maintenance and Acceptability

6.1. Introduction

One of the most critical challenges for RCS systems is to reduce maintaining water consumption while keeping the sanitary wares clean and hygienic, and odorless. In such case, controlling the challenges which urination may cause in toilet seats and men urinals is essential.

Urination is a natural process and the most frequent form of excretion in human beings. The urinary bladder of an adult person may hold as much as about 500 milliliters of urine, with the desire to urinate usually arising when the bladder contains about 150 milliliters. Then, as urine volume increases to 300 milliliters or more, the sensation of fullness becomes increasingly uncomfortable (Hashemi et al. 2015a, Hashemi et al. 2015b, Shier et al. 2016). Therefore, a healthy adult may urinate about 150 to 500 milliliters of urine 4 to 8 times a day depending on the amount of fluids ingested (Fleisher and Ludwig 2010).

Accordingly, Men's urinals are commonly used to provide a facility which takes up less space and can reduce the water consumption (0 - 4 l/flush) compared to conventional toilets (6 - 13 l/flush). Urinals can be categorized as conventional urinals (2 - 4 l/flush), low-flush urinals (0.5 - 0.8 l/flush) and water-less urinals (0 l/flush) according to the amount of water used each time they are flushed (Vickers 1999).

In RCS systems, waterless urinals should be utilized due to their two crucial advantages over water-flushed urinals: water saving and their potential to be able to collect undiluted urine which can be used to produce fertilizer. In this case, for waterless urinals being utilized, urine scale formation and odor are two main challenges which should be solved sustainably. Many kinds of toilets use water to dilute and flush down urine to avoid these issues (Larsen et al. 2001).

Nevertheless, the dilution of urine using flushing in waterless sanitary systems for maintenance purposes leads to much water being consumed and produces significant amounts of wastewater. Thus, many surveys show that waterless urinals are not accepted because of different practices or cultural notions of cleanliness (Hashemi et al. 2015b).

Flushing urine with high Total Dissolved Solids (TDS) water can increase urine scale formation depending on the characteristics of the flushing water, which in turn increases the potential for blockage in traps and connecting pipes. One good example of this concept is sanitation practices in Hong Kong. As the majority of people are proudly using seawater for flushing as an alternative water resource, the demand of using waterless urinals is not being felt (Chau 1993). Muslim societies also do not accept waterless urinals, owing to cultural ideas causing them to use water for body and facility cleansing practices (Hashemi et al. 2015b).

Overcoming barriers mentioned above is required to provide a sustainable maintenance for RCS systems and improve their acceptability. In this chapters, we are proposing methods for overcoming urine scale formation using rainwater as well as optimizing the amount of flushing water for maintenance usage according to the amount of urination.

6.2. Identification of Urine Scale Problems in Urinals and the Solution Using Rainwater

Although urine and its chemistry have been studied by many researchers in the area of medical science, the chemical behavior of urine and flushing water mixed in urinal systems (including their transport and storage) has not yet been studied at any significant technical depth, the same goes for the causes of scaling and possible solutions by using advantages of roof-harvested rainwater such as no or too little TDS or demand of too little energy for treatment (Dao et al. 2013, Han and Mun 2011).

Accordingly, here, factors that affect urine scale formation are studied by conducting laboratory tests using several types of water with different TDS including seawater, high salinity groundwater, groundwater, tap-water, and rainwater. Also, the ramification of the results on the operating practices of urinals and water supply systems are discussed.

6.2.1. Materials and Methods

Fresh urine was collected from the men’s public waterless urinals installed in Seoul National University (SNU) for research purposes. Seawater was collected from the West Sea of Korea and groundwater was collected from two different places. One was from a residential well in Incheon City which is a coastal city and slightly affected by salt intrusion, and the other from

Bongeunsa temple, located in downtown Seoul. Tap-water was collected from the Seoul Metropolitan water supply system. Rainwater was collected from the rainwater harvesting tank of SNU.

The fresh urine was used immediately after collection for the experiment. The different kinds of water were mixed with urine in different dilution ratios (1 unit urine to 1, 3, 8 and 10 units of diluting water) inside plastic tubes to make up 150 ml of volume in total, and were shaken intensively for 10 seconds. The samples were then left for 30 minutes to react before they were used for sample characterization. Using this sampling process, three different sets of samples were prepared for measurement.

Table 6.1 presents the physicochemical characteristics of all materials used in the experiment. The chemical composition of urine was examined based on the concentration of calcium, magnesium and phosphate ions, which were investigated due to their essential role in forming urine scales.

Table 6.1. Characteristics of Fresh Urine and Flushing Water

Materials	TDS (mg/l)	pH	Concentration of Ions (mg/l)		
			Ca^{2+}	Mg^{2+}	PO_4^{3-}
Fresh Urine	7683	6.4	165.3	98.2	473.3
Seawater	43216	8.9	553.1	4473.7	28.6
Salty Groundwater	13698	8.4	289.2	155.4	39.2
Groundwater	805	7.9	86.9	88.3	12.8
Tap-water	109	7.2	16.3	4.6	6.3
Rainwater	12	6.2	1.2	0.9	0.1

A dilution ratio 1:1-10 was chosen because the amount of flushing water is 0.5-4 l/flush while a healthy man usually urinates a maximum of about 500 ml (Hashemi et al. 2015a, Hashemi et al. 2015b, Larsen et al. 2001, Shier et al. 2016). The chemical concentration of the samples was measured following US EPA standards using a UV/Visible Spectrometer, model HS-3300 (USEPA 1979). For pH, temperature and TDS measurements, Aquaread Aquaprobe model AP-2000 was used.

The concentrations of phosphate, calcium, and magnesium ions were measured for 6 hours, starting from the time of sample preparation, at intervals of 1 hour. After 6 hours, the concentration of ions was shown not to change significantly. Also, changes in pH with time were investigated because pH has a significant effect on urine scale formation (Udert et al. 2003). To study the effects of temperature, samples were left in a Cole-Parmer Standard Benchtop Chilling/Heating Block, model 100-230 VAC equipment to obtain temperatures of 5, 10, 20, 30 and 40 degrees Celsius for 30 minutes and then went undersampling for chemical ion concentration measurement.

Sampling for chemical concentrations at each temperature was done while the sample was still in the chilling/heating block. This was done to ensure the effects of temperature were accurately modeled. Finally, TDS was measured for each of the dilution ratios (using the different water types) and each was compared with pure urine results observed. For chemical measurements, experiments were triplicated and an arithmetic mean was taken as the final result. The standard deviation of the results was used as an indicator of the error bars.

6.2.2. Results and Discussion

The urine scales form as a result of supersaturating minerals affected by many factors such as time, pH, and temperature, which can affect the solubility of solid ions. Moreover, the concentration of total dissolved solids (TDS) can directly influence scale formation and the precipitation process. The material of the sanitary matters also may have influences on the formation and type of the urine scale (Hashemi et al. 2015a).

Based on prior studies, such as Udert et al. (2003), the urine scale formation process mainly occurs because supersaturated Ca^{2+}, Mg^{2+}, and PO_4^{3-} ions precipitate as calcite ($CaCO_3$), struvite ($MgNH_4PO_4 \cdot 6\ H_2O$) and hydroxyapatite ($Ca_5(PO_4)_3OH$) (Hashemi et al. 2015b). Although chemical measurements and analysis were done for Ca^{2+}, Mg^{2+}, and PO_4^{3-}, only the results for calcium ion are presented in this paper because similar results and trends are found in the magnesium ion and phosphate.

6.2.2.1. Precipitation Process

Figure 6.1 illustrates how the precipitation of calcium ions proceeded to decreases with time for different water types at the dilution ratio of 1:8. The Ca^{2+} concentration decreases with time for pure urine and all water types because of Ca^{2+} precipitation and becomes stable after 6 hours. The difference in Ca^{2+} concentration shown the amount of precipitation that is occurring.

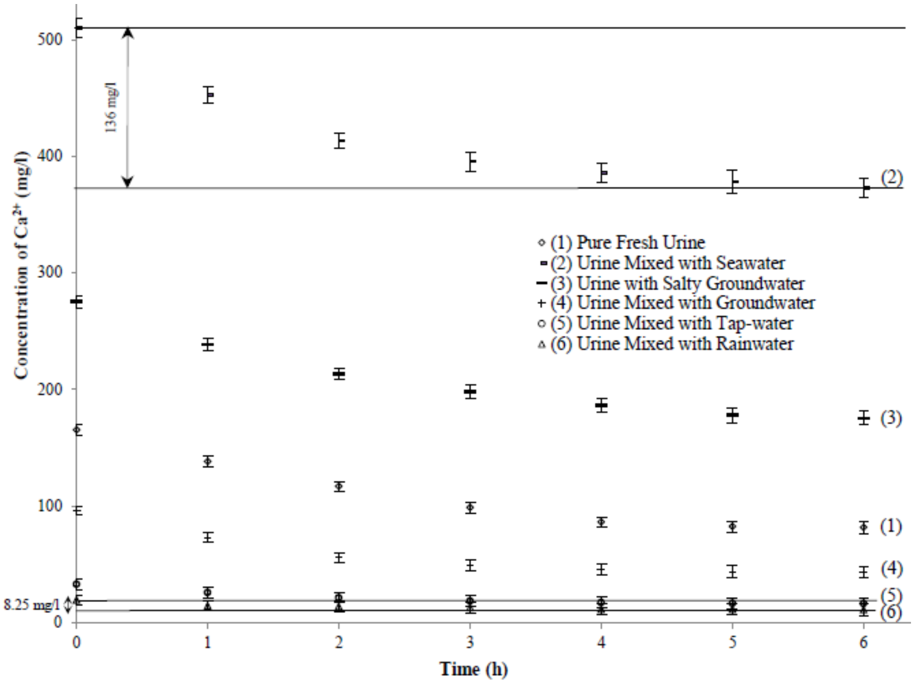

Figure 6.1. Reduction of Ca^{2+} for Different Types of Flushing Water (Dilution Rate = 1:8; Temp = 25 ^{o}C)

After about 6 hours, calcium precipitation in urine dilution with seawater and rainwater was about 136 mg/l and 8.25 mg/l respectively. This shows that not only was the amount of precipitation in the rainwater diluted sample significantly smaller than the sample diluted with seawater, but also the precipitation process in urine diluted with seawater was about 16 times faster.

6.2.2.2. Change of pH with Time and the Effect on Precipitation

Variations in pH of samples with time are shown in figure 6.2 for the dilution ratio of 1:8. The pH of all samples increased because of a hydrolysis process of urea, described by equation 4.1. However, only in the case of urine diluted with rainwater did the pH stays below 9.

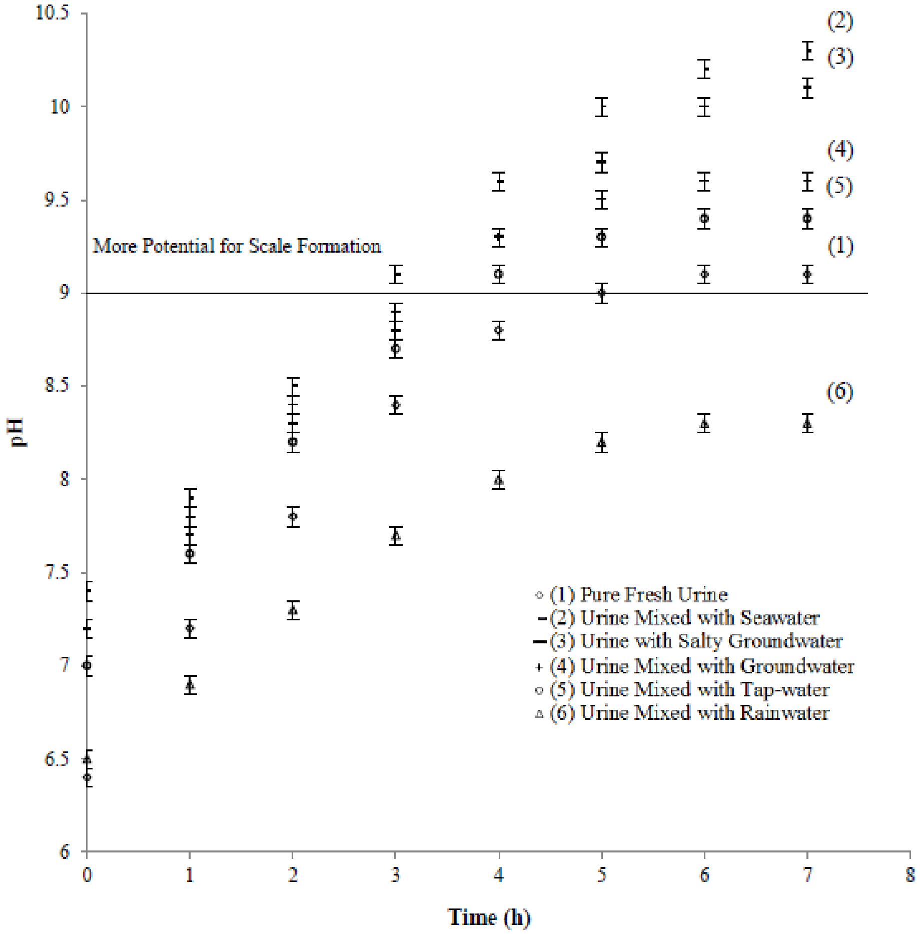

Figure 6.2. Change of pH of Samples with Time (Dilution Rate = 1:8; Temp = 25 ^{o}C)

Studies show that in a solution with a pH higher than 9, it typically leads to supersaturation of chemical ions and their eventual precipitation (Udert et al. 2003). This study shows that rainwater modifies the pH of the sample and so was urine is mixed with rainwater the potential for scale formation is reduced.

6.2.2.3. Effect of Temperature on Scale Formation

Figure 6.3 illustrates the effect of temperature on calcium precipitation in the dilution ratio 1:8. The concentrations of all measured ions increased with increasing temperature; thus indicates that the scale formation process was much slower at high temperatures, as the solubility of dissolved solids increases with temperature.

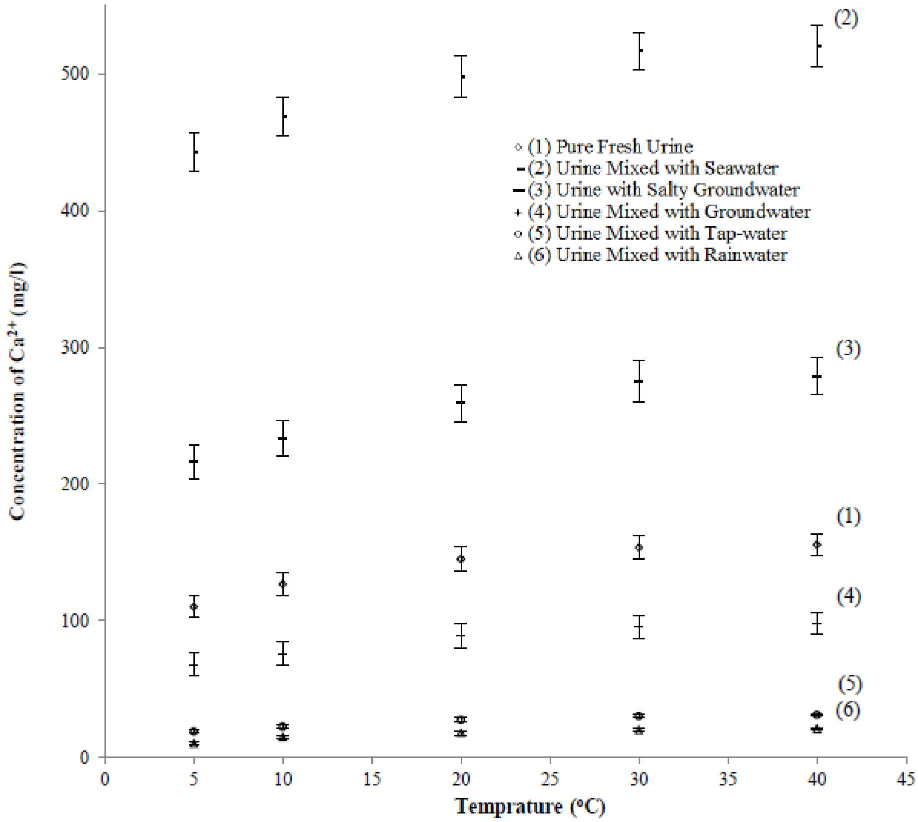

Figure 6.3. Effect of Temperature on Precipitation of Ca^{2+} (Dilution Ratio is 1:8)

These results suggest that the observed practice of using ice cubes in some public urinals is not recommended. Instead, keeping the urinals warm can help reduce the amount of scale formation. The results also indicate that seawater and salty groundwater are affected most by temperature.

6.2.2.4. Effect of Dilution Ratio (TDS)

TDS indicates the amounts of dissolved solids; water with higher TDS can produce more scales. Figure 6.4 presents the results of TDS measurements in urine diluted with different types of water with dilution ratios of 1:1, 3, 5, 8 and 10.

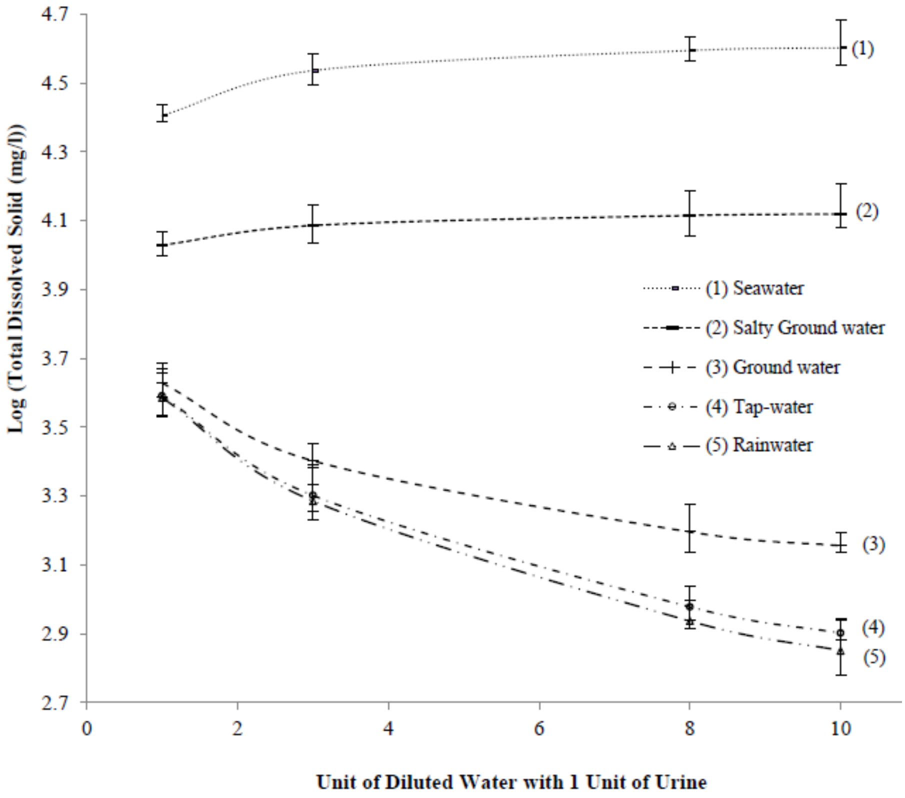

Figure 6.4. TDS Measurement Results for Urine Diluted with Different Dilutions

In the specific cases of urine diluted with seawater and salty groundwater, TDS increases with the dilution ratio, which could increase scale formation potential. Conversely, dilution of urine with groundwater, tap-water, and rainwater resulted in a completely different trend; they decreased TDS and the potential for scale formation as well.

Overall, mixing urine with water which has a lower TDS than itself can reduce the amount of TDS of the mixed solution. Although diluting urine with higher dilution ratios using groundwater and tap-water can reduce the TDS of the final solution, using rainwater is the most effective in reducing urine scale formation as it has the least amount of TDS compared to other types of water.

Using rainwater also has other advantages as it can be collected via rainwater harvesting systems, free of charge thus requiring little or zero energy to produce or abstract the treatment processes unlike other flushing waters (Dao et al. 2013).

6.2.2.5. Discussion

The behavior of urine in scale formation due to the pH and the types of flushing water can be explained well with a pC – pH diagram for Ca^{2+} solubility as in Figure 6.5. By considering the calcite formation process and the carbonate hydrolysis process (equation 6.1), as well as the molarity of calcium (40078 mg/mole), equation 6.2 can be developed. The dividing line for saturation is thus calculated. Precipitation occurs when the conditions are above the line (Stumm & Morgan, 1996).

$CO_3^{2-} + H_2O \leftrightarrow HCO_3^- + OH^-$; $\left(K\ (at\ 25\ ^{o}C) = \frac{[H^+][CO_3^{2-}]}{[HCO_3^-]} = 10^{-10.32}\right)$

(Eq. 6.1).

$$-pC = \log[Ca^{2+}] = \log\left(\sqrt{10^{-8.48} \times \left(1 + \frac{10^{-pH}}{10^{-10.32}}\right)} \times 40078\right) \qquad \text{(Eq. 6.2).}$$

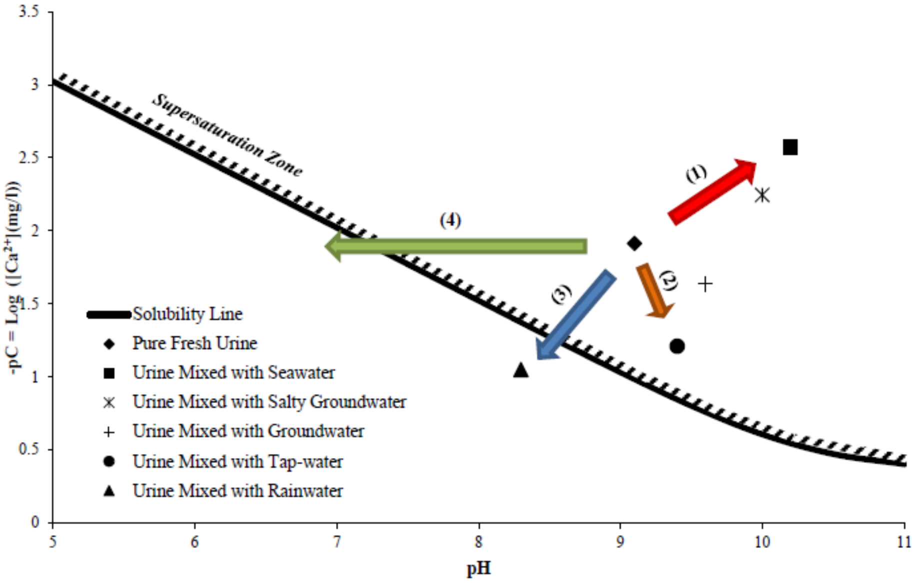

Figure 6.5. Precipitation Process of Calcium versus pH (Dilution Rate = 1:8; Temp = 25 ^{o}C)

The symbols in the graph show the pH and concentration of Ca^{2+} of pure urine and urine mixed with different kinds of flushing water respectively, and all stabilized after 6 hours. The results suggest that urine mixed with rainwater is under-saturated, while others are in the super-saturation zone.

This diagram can serve as a basis for criticism of several practices, as well as a suggested solution. Flushing with a high TDS water such as seawater, which is practiced by Hong Kong authorities (arrow 1), means moving into the super-saturation zone where urine scale formation will increase. This is not a desirable practice considering the urine scale formation. Although flushing with tap-water (arrow 2) reduces precipitate composition (Udert et al. 2003), it increases the pH and required high volumes of water to make it unsaturated. Whereas flushing by rainwater (arrow 3) results in less Ca^{2+} concentration and lower pH, the Ca^{2+} is under-saturated and causing scales not to form in this region. Another way to reduce urine scale formation is to add a weak acid (arrow 4) to the under-saturated zone. The amount of added acid can easily be calculated with simple chemistry.

6.3. Identification of Urine Scale Problems in Urinals and the Solution Using Rainwater

In the case of fresh urine, food and drugs have a substantial impact on its smell, as such compounds can be excreted without being entirely broken down (Hashemi and Han 2017a, Hashemi and Han 2017d). However, the primary challenge when it comes to odor in sanitation is related to urine that remains on the sanitary ware or urine that cannot be drained successfully (Zhang et al. 2013). In these cases, the odor is caused primarily by the ammonia released by the enzyme urease (equation 4.1).

During storage of pure (undiluted) urine, the urea present is transformed into ammonia via a process that uses the enzyme urease (Udert et al. 2006). The produced ammonia reacts with water and equilibrium of ammonium ions and hydroxide is reached, which increases the pH of the urine. Because the pK_a of this equilibrium is 9.22, at a pH > 9.22, the primary compound formed is ammonia, which dissolves in water by forming hydrogen bonds with water molecules as well as producing ammonium (Hashemi et al. 2016, Udert et al. 2006).

Because of evaporation and the fact that oxygen has a higher electronegativity than nitrogen, the hydrogen bonds between ammonia and water molecules easily break, causing ammonia to be released as a gas, generating a strong odor of urine (Hashemi et al. 2016). Therefore, by studying the governing factors of urine odor, it might be possible to adjust the characteristics of the diluting water as well as the water:urine dilution ratio to overcome the odor of urine, which may lead to ideas for reducing water consumption for the different urine excretion practices.

Therefore, in this section, the effect of the pH and temperature of the diluting water with regards to the minimum dilution ratio required to overcome urine odor is determined. Also, a method for reducing water consumption in actual sanitation practices is suggested.

6.3.1. Materials and Methods

6.3.1.1. Raw Materials

Pure urine samples were collected from men's waterless urinals installed in Building 35 of Seoul National University into new and clean 10 L plastic containers. The whole system was thoroughly cleaned prior to the study. The urine came from men who were 25 – 35 years old. The urine samples were stored in an air-conditioned room at 22 °C for 20 days.

The pH and initial ammonia concentrations of the samples were measured daily for 20 days after collection following USEPA standards (USEPA 1979)using an Aquaprobe model AP-2000 (Aquaread Ltd.) and a UV/Visible spectrometer (model HS-3300 made by Humas Co.) respectively. No significant changes were detected in these measured characteristics after 17 days, thus the sample was deemed stable. After stabilization, the Total

Dissolved Solids (TDS) and temperature of the sample were measured by the Aquaread Aquaprobe apparatus mentioned above.

To dilute the urine samples, tap water from the Seoul metropolitan water supply system was used. The pH, ammonia concentration, TDS, and temperature of the tap water samples were measured right after sampling using methods similar to those applied to the urine samples. Table 6.2 presents the initial characteristics of the raw materials.

Table 6.2. Initial Characteristics of the Raw Material Samples

Samples	pH	Ammonia Concentration (mg/L)	TDS (mg/L)	Temperature (°C)
Urine	9.8 ± 0.2	6152	7683	20 ± 3
Tap Water	7.4 ± 0.2	Not Detected (<0.001 mg/L)	118	15 ± 2

6.3.1.2. Sampling Procedure

To investigate the effect of the pH and temperature of the diluting water on the odor of pure and diluted urine, 396 water samples with different pH values and temperatures were prepared using 100 mL glass samplers. The pH of the diluting water samples was adjusted to range from 5 to 10 at 0.5 intervals using 99.5% citric acid and 1 M sodium hydroxide solution made by Daejung Co. To adjust the temperature of the diluting water samples, they were inserted into a Cole-Parmer Standard Benchtop Chilling/Heating Block (model EW-44175-00), at temperatures ranging from 5 °C to 30 °C, in 5 °C intervals.

By assuming 500 mL as for the possible amount of urination and considering the water consumption of different types of toilets as described by Hashemi and Han (2017a), dilution ratios of 0, 0.5, 1, 4, 8, and 26 units water to 1 unit of urine were used. For the case of a water:urine dilution ratio of 0:1, which represents waterless practices, the pH and temperature were adjusted for the pure urine samples directly.

6.3.1.3. Characterizing Odor of Samples Using Threshold Odor Number

Immediately after preparation, the samples underwent Threshold Odor Number (TON) measurement following USEPA-approved Standard Method 2150 B (APHA/AWWA/WEF 2012). Twenty people participated as smell testers to execute the TON measurement. The testers consisted of four individuals each from Africa, the Americas, Asia, Europe, and Oceana. Each set of four testers included two males and two females, who were aged 25 to 32 years, were healthy and had no nasal problems or difficulty regarding their sense of smell. All study participants provided informed consent, and an appropriate ethics review board approved the study design.

6.3.2. Results and Discussions

6.3.2.1. Effect of the pH of Diluting Water and Dilution Ratio on Urine Odor at Various Temperatures

Figure 6.6 presents the effect of dilution ratio and pH of diluting water on TON of urine when the temperature of the diluting water was 15 °C. Similar results were observed for diluting water at other temperatures.

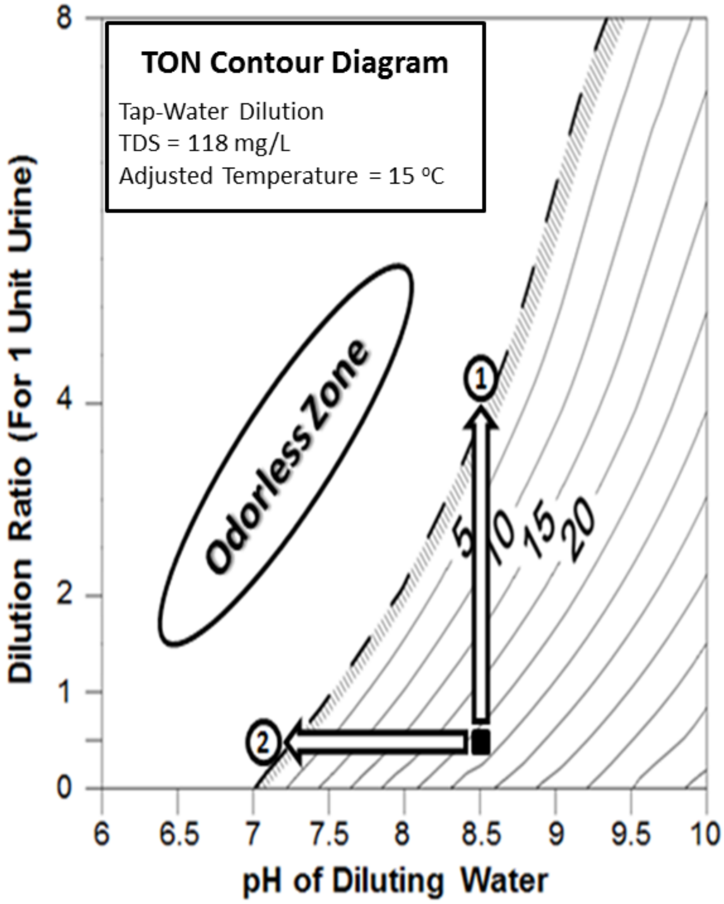

Figure 6.6. Effect of the pH of diluting water and dilution ratio on TON of urine when the temperature of the diluting water was 15 °C. The Odorless Zone is attainable by increasing the dilution ratio (Arrow 1) and/or reducing the pH of the diluting water (Arrow 2).

In the case of water with pH < 7, no smell was detected at any dilution ratio. Similarly, for the dilution ratio of 26 units water to 1 unit urine, no smell was detected at any pH. Results show that at a constant temperature for diluting water with an adjusted pH, there is a minimum dilution ratio for which TON is zero. In addition, for certain sanitation practices, e.g., using 0.5 units of water with pH = 8.5 to dilute 1 unit of urine as presented in Figure 6.6, when the temperature of diluting water is constant, there are two ways to overcome the smell: one is to increase the dilution ratio up to 4 units of water for 1 unit of urine (Arrow 1); the other is to lower the pH of the diluting water to approximately 7.2 (Arrow 2).

For overcoming the urine odor in the condition presented in Figure 6.6, by increasing water consumption, eight times higher dilution ratio is required (from half a unit of water to four units of water for one unit of urine). This practice is not suitable as it increases water consumption. However, by using water with a pH lower than 7, it is possible to keep urine free of odor. In the case of waterless practices, the pH reduction can be made by spraying weak acids directly inside the sanitary ware.

6.3.2.2. Effect of the Temperature of Diluting Water and Dilution Ratio on Urine Odor at Various pH Levels

Figure 6.7 presents the effect of dilution ratio and the temperature of diluting water on TON of urine when the pH of the diluting water was 8.5. Similar results were observed for diluting water with pH > 7.

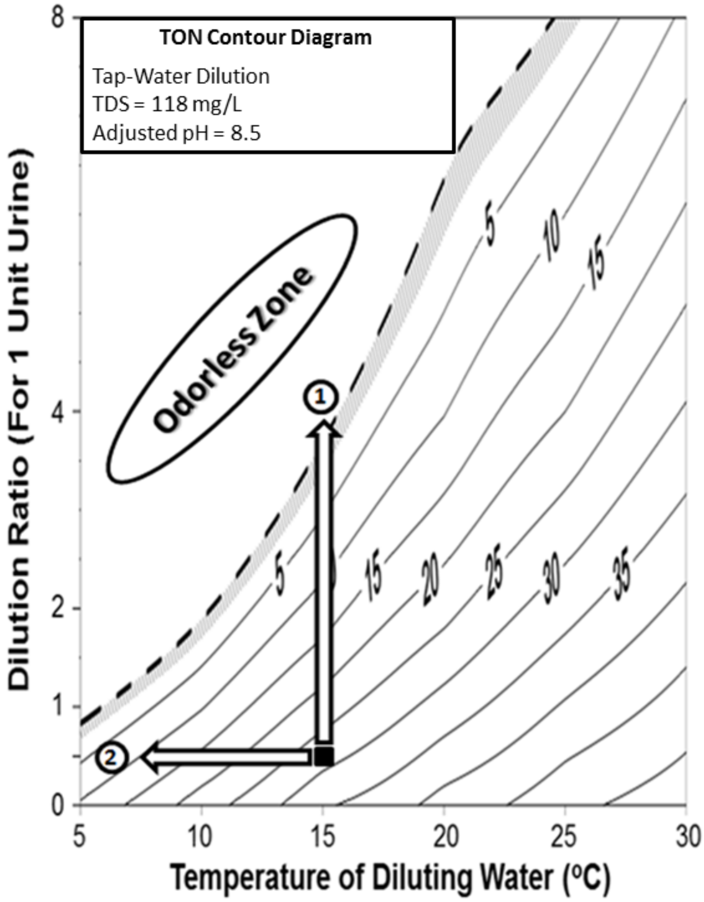

Figure 6.7. Effect of the temperature of diluting water and dilution ratio on TON of urine when the pH of the water was 8.5. The Odorless Zone is attainable by increasing the dilution ratio (Arrow 1) and/or reducing the temperature of the diluting water (Arrow 2).

Analogous to the case of constant diluting water temperature, results show that when the pH of diluting water is constant, at a specific temperature, there is a minimum dilution ratio at which urine odor is removed. Furthermore, for certain sanitation practices, e.g., 0.5 units of water at 15 °C for 1 unit of urine as presented in Figure 1, when the pH of water is constant, there are two ways to overcome the smell: one is to increase the dilution ratio (Arrow 1), and the other is to reduce the temperature of the diluting water (Arrow 2).

When diluting with high-temperature water, overcoming the smell is more difficult and requires higher water consumption. Therefore, flushing or diluting with hot water may not be suitable. These results also explain why stronger urine odors are detected in sanitation systems during summer than in the winter.

Lowering water temperature is effective in reducing urine smell. However, it cannot eliminate it. As such, slightly increasing the dilution ratio can be more efficient in removing the odor of urine. However, because increasing water consumption is undesirable, utilizing water with pH > 7 may not be useful.

6.3.2.3. Effect of the pH and Temperature of Diluting Water with Constant Water Dilution on Avoiding Urine Odor

Figure 6.8 presents the effect of the pH and temperature of diluting water on TON of urine when the dilution ratio was four units of water for one unit of urine. Similar results were observed for other dilution ratios less than 26 units water to 1 unit urine. Again, results show that for certain sanitation practices, e.g., using water with a temperature of 15 °C and pH of 9, when the dilution ratio is constant, there are two ways to overcome the smell: one is to decrease the temperature (Arrow 1), and the other is to reduce the pH of the diluting water (Arrow 2).

In this practice, during high-temperature seasons, the temperature of the water must be lowered by approximately 15 degrees (from 25 °C to about

10 °C). In this case, as an example, for one liter of water, the required energy is calculated as approximately 0.0175 kWh (Hashemi and Han 2017a).

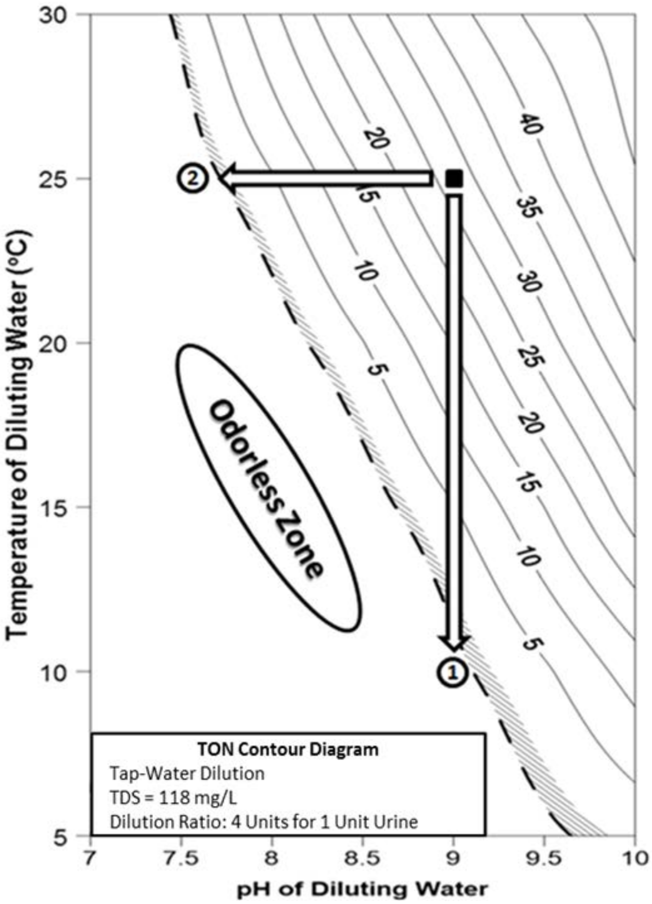

Figure 6.8. Effect of the pH and temperature of diluting water on TON of urine when the dilution ratio was fixed at four units of water to one unit of urine. The Odorless Zone is attainable by reducing the temperature (Arrow 1) and/or pH (Arrow 2) of the diluting water.

Therefore, by assuming 100 flushes per day for a men's public urinal, which consumes 4 liters of water per flush, the annual cost of energy is calculated as about US$241 per year based on 2015 energy prices in the United States (Hashemi and Han 2017a). Concerning the annual costs for only one set of men's public urinals and the reduction in water temperature to avoid urine odor, this practice may not be economical.

The temperature of the diluting water in some men's urinals can be lowered by putting ice cubes inside the sanitary ware. Although this may be effective in reducing urine odor, it can increase the potential for urine scale formation and cause clogging in pipeline systems because it reduces the solubility of scale- forming compounds (Hashemi et al. 2015a, Hashemi et al. 2015b).

However, by reducing the pH of the diluting water, it is possible to control the odor of the urine by utilizing weak natural acids such as acetic acid (vinegar) or citric acid (lemon juice), which seems to be a more sustainable and economical practice (Hashemi and Han 2017d). The amount of acid to add can be calculated based on chemical stoichiometry.

6.3.2.4. Reducing Water Consumption in Sanitation Systems by Controlling Odor of Urine

Based on the presented results, the amount of flushing water should consider both the characteristics of the flushing water and the amount of urination to overcome odor with the exact required amount of water. As the amount of flushing water is constant most of the time, the dilution ratio for most of the sanitation practices is higher than required to overcome the odor, which means that water is often being wasted, as presented in Figure 6.9.

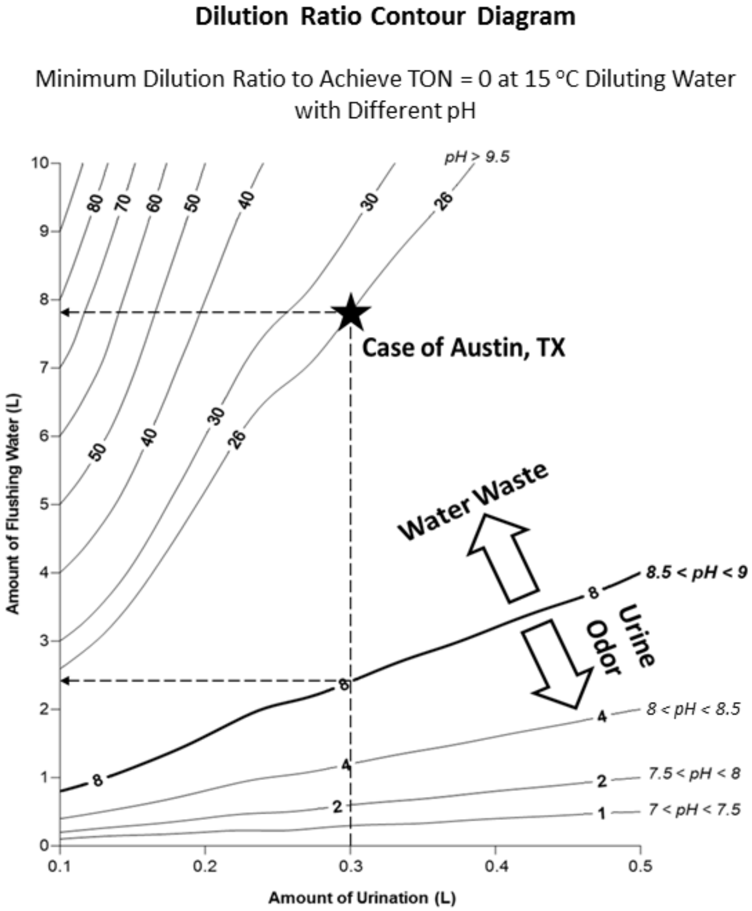

Figure 6.9. Diagram of minimum dilution ratio for different pH ranges of diluting water in sanitation systems based on the actual amount of urination and flushing water

Thus, by lowering the pH, the required dilution ratio to avoid urine odor can be lowered, which reduces water consumption in sanitation systems. For example, the pH of tap water in Austin, TX, USA is reportedly about 9.6 (Hashemi and Han 2017a). Based on Figure 6.9, 26 units of water with such a high pH are required per 1 unit of urine to make the urine odorless. However, by adjusting the water to 8.5 < pH < 9, the required water consumption when flushing 0.3 L urine may be reduced, from 7.8 L to 2.4 L.

6.4. Conclusions

According to our studies, urine scale formation is affected by Ca^{2+} concentration and pH, which can be explained by a simple pC–pH diagram. To avoid scale formation, urine should be flushed with low TDS water such as rainwater or lower pH water by adding a weak acid. Regarding scale formation, flushing with seawater as practiced in Hong Kong is not a good practice, although it may seem practical to use an alternative water resource. Higher temperature can reduce the urine scale formation potential by increasing solubility.

Our results also suggest that observed sanitation practices such as putting in ice cubes in some public urinals, is not a good either regarding urine scale formation, though it may help reduce water consumption and smell. In addition to the increasing importance of rainwater as a sustainable water supply in many parts of the world, it also has a high possibility to solve the urine scale problems because of its low TDS and ability to reduce the pH of the final solution. Furthermore, the findings of this study can also support the use of low-flush urinals in Islamic countries as problems associated with urine scale can be reduced by using rainwater for flushing.

On our way to find a solution for removing the odor of urine in RCS systems, the effects of the pH and temperature of the diluting water and dilution ratio on reducing the odor of urine were investigated. Results show that utilizing diluting water with a pH less than seven is very efficient in avoiding odor. Reducing the temperature also has a positive effect; therefore, flushing with hot water is not recommended.

In WOS sanitation systems where the amount of flushing water (indicated as dilution ratio) cannot be changed, lowering both temperature and pH of the flushing water can help in avoiding odor. However, not only is reducing the temperature uneconomical as it may incur expenses from energy consumption, but it may also cause other problems such as promoting the formation of urine scale.

Instead, pH reduction using weak natural acids should be considered an easy, sustainable, and efficient management method for overcoming odor. In waterless sanitation practices, spraying these weak acids inside the sanitary wares can be useful for managing odor. Results also yield that for a specific pH range or temperature of the diluting water, a minimum dilution ratio is needed to avoid odor. As the amount of urination is not taken into account in sanitary systems and the amount of flushing water is usually constant, excessive amounts of water often are being consumed, given the amount of urine in most current sanitation systems.

Results from our study could lead to a redesign of systems for optimizing water usage based on the volume of urination. Smart systems using Information Technology (IT) could be utilized to measure the amount of urination each time and subsequently estimate the sufficient amount of water that would be needed for each flush, of course, considering the temperature and pH of the water. As seen in the case study of Austin, by reducing the pH of the diluting water, it is possible to have sustainable and water-saving sanitation management.

7. Efficiency of the RCS System in Field

7.1. Introduction

As it is explained before, source separated sanitary matters have emerged as a promising potential fertilizer because they are ubiquitous and cheap (Han and Hashemi 2017, Han et al. 2016). Historically, farmers have mostly used their urine to grow crops for their consumption (Bond et al. 2013, Han and Kim 2014, Hashemi and Han 2017d). Recently, higher-density pilot systems have been constructed to collect and apply urine and feces to fields (Berndtsson 2006, Chrispim et al. 2017, Rossi et al. 2009).

In previous chapters, we proposed our way to make urine and feces as attractive fertilizers by optimizing their nutrient profile with low pathogen content. Several studies have examined the effect of sanitary matters collected in ROS systems on plant growth (Guzha et al. 2005, Pradhan et al. 2007), but most have not considered the engineered systems for collecting and transporting urine as fertilizer.

In ROS systems, once collected, urine and feces are transported by either separate pipes or by truck. Both retrofitting separate piping and tracking (Drangert 1998) not only can be expensive but also can face serious problems like clogging or urine scale formation. Therefore, making a sustainable RCS system which can sustainably treat the sanitary matters onsite can be a significant step ahead for overcoming the mentioned barriers. Thus making the system applicable in developing countries can be a noteworthy step toward SDG 6.

In this chapter, we report the trial of installing our designed RCS system in an urban farming center to examine its efficiency. In this system, urine and feces are gathered separately in specific reactors and being treated onsite to be utilized as fertilizer. Finally, the treated materials are applied to the soil to compare their effect of growing white radish with commercial fertilizer.

7.2. Materials and Methods

7.2.1. *TORRY*: An Innovative RCS System

TORRY (土利), which means beneficial for soil in the Korean language, is an RCS system which is manufactured under the idea of not to consider sanitary matters as waste but to treat them as valuable resources. As presented in figure 7.1, it has three main parts: toilet seat on the top which is well managed to be always in a hygienic state, urine reactor, and feces reactor both located at the bottom section.

The system has been installed in Cheonsu Urban Farming Center located in Seoul, Republic of Korea (37°38′47″N, 127°05′7″E) and operation started from May 6, 2017, at 11:00 am KST.

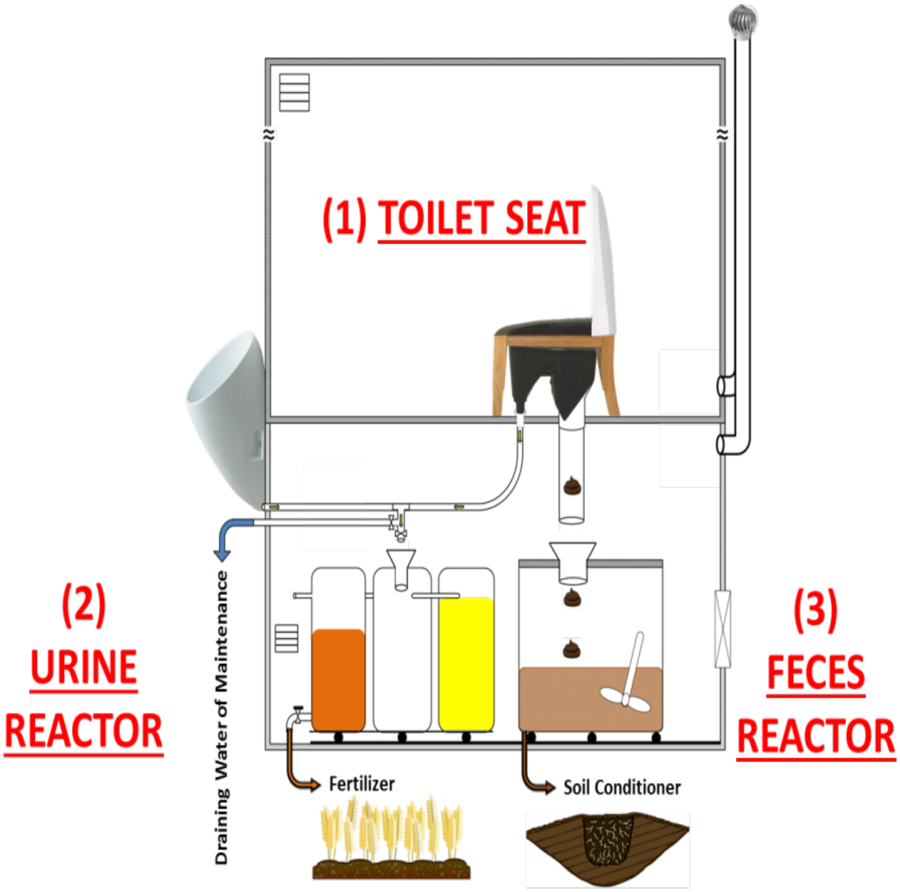

Figure 7.1. Composition of *TORRY* (The Latest Design)

7.2.1.1. The Seat and Maintenance

Sanitary matters are being separated efficiently using a separator as presented in figure 7.2. The seat is designed to be entirely similar to the conventional toilet seats, and the separator can be easily removed from the system to be cleaned after each event or a period. Then, the gathered urine and feces are stored and treated to be utilized as fertilizer and soil conditioner.

Figure 7.2. Seat and Separator of *TORRY*

As presented in figure 7.3, required water for maintenance and hand-washing is provided using rainwater harvesting system and the produced gray water is being treated and recycled in-situ (Han et al. 2016). Therefore, the system is expected to be a very high water self-sufficient one as well as releasing no wastewater.

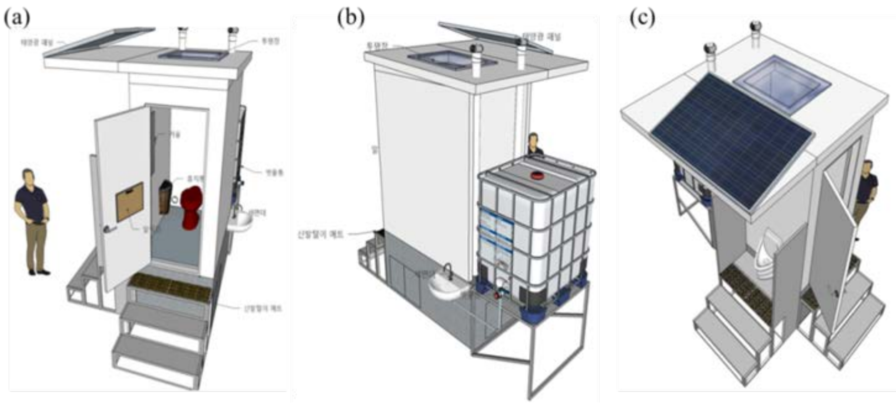

Figure 7.3. (a) Toilet Seat and Sanitary Wares, (b) Rainwater Harvesting System, (c) Solar Energy Supply System

Required energy is being supplied using solar cells. As mentioned before, the toilet seat and maintenance part is being well managed to be always in a hygienic state.

7.2.1.2. The Urine Reactor and Smart TORRY *Urine Bank*

As presented in figure 7.4, in the demonstrated system, urine is gathering inside a tank-in-series treatment system including six 20-L tanks. The number of tanks can be changed based on the amount of usage.

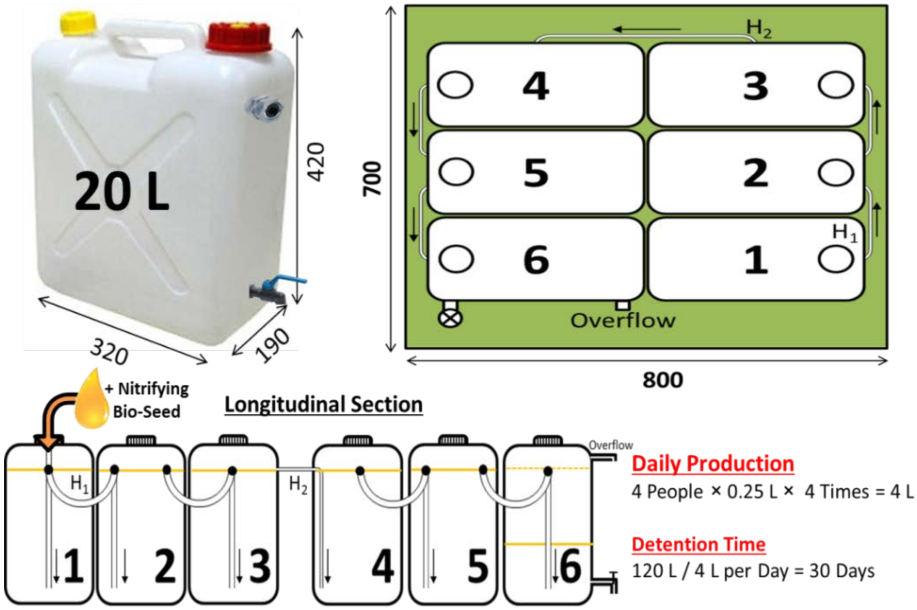

Figure 7.4. Urine Reactor Compositions and Characteristics

The materials for making the reactor is very cheap and feasible everywhere. The treatment of urine is being done through the process explained in chapter 4 to prevent odor production as well as preparing it to be utilized as fertilizer after reaching to the last tank (Hashemi et al. 2016).

As presented in figure 7.5, the reactor can also be equipped with IT systems to make the maintenance easier. To make it usable during winter, heating pipes can be installed to obtain the favorable temperature.

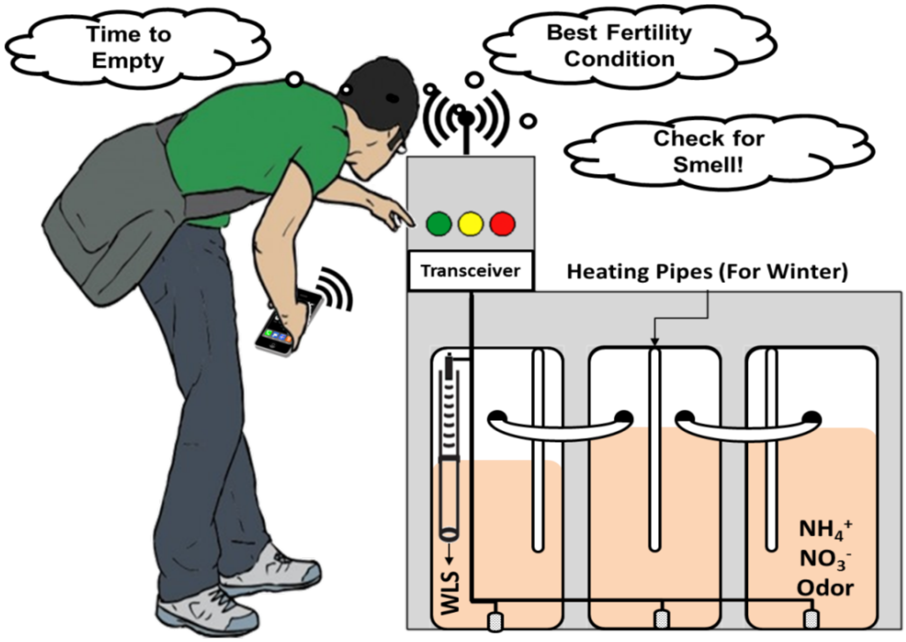

Figure 7.5. The I.T. Maintenance Assisted Urine Reactor

As presented in figure 7.6, the design can be very flexible, nice looking, and compatible with the available space, inside or outside of the main RCS structure.

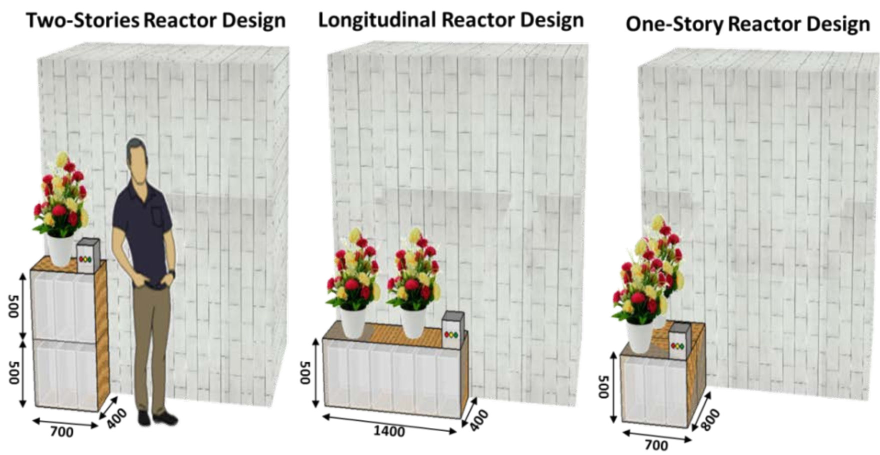

Figure 7.6. Nice Looking Smart *TORRY* Urine Bank

7.2.1.3. The Feces Reactor Characteristics

Figure 7.7 shows the schematic view of the feces reactor which has a simple design. In this reactor, the gathered feces is treated for volume reduction as well as C/N ratio optimization through a biochemical assisted composting process as explained in chapter 5 (Hashemi and Han 2017b, Hashemi and Han 2018). The final product can be utilized as a soil conditioner.

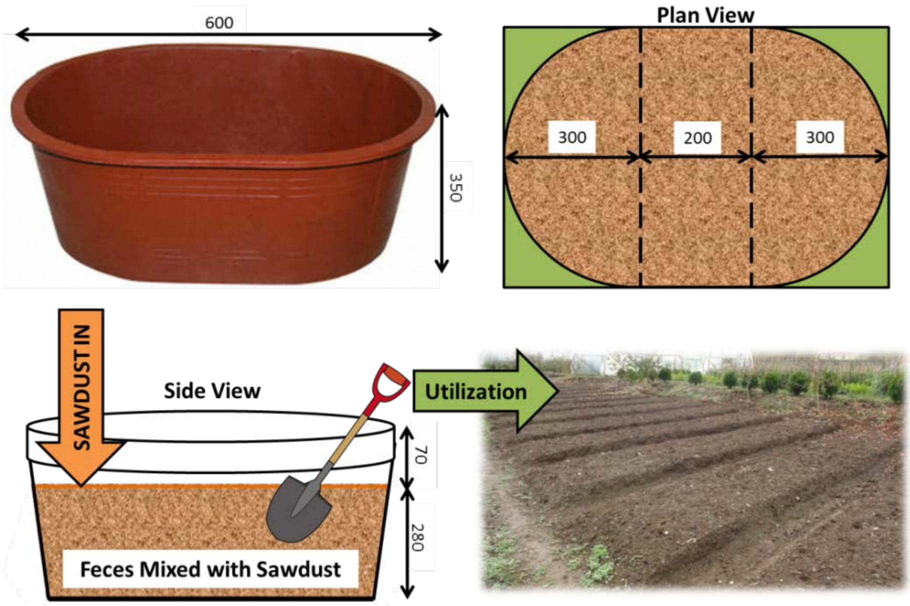

Figure 7.7. Feces Reactor Compositions and Characteristics

7.2.2. Raw Materials and Sampling Procedure

Treated urine and composted feces are gathered from *TORRY*. Commercial fertilizer named Hanpanseung is obtained from Samhwa company, located at Namyangju City, Gyeonggi Province, Republic of Korea.

The amount of 100 kg soil samples, which described in chapter 4, is gathered. Thirty kilograms of it were kept intact to be used as control (Sample 1). The rest is divided into four 20 kg samples treated in four different treatment ways as mixed with 10 kg fertilizer (Sample 2), 10 kg treated urine (Sample 3), 10 kg treated feces compost (Sample 4), and a mixture of 5 kg treated urine with 5 kg treated feces compost (Sample 5). To make homogenized soil samples, mixing procedure has been done using a C-Mac Soil Mixer with 0.5 m^2 capacity manufactured by C-Mac Industries (Aust) Pty Ltd located at Girraween, New South Wales, Australia has been done for 30 minutes for each sample.

As presented in figure 7.8, using the prepared soil samples, five planting paddies are prepared in the size of 1.4m × 2m to plant the white radish. The seeds are provided by World-Seed Company located at Yongin City, Gyeonggi Province, Republic of Korea.

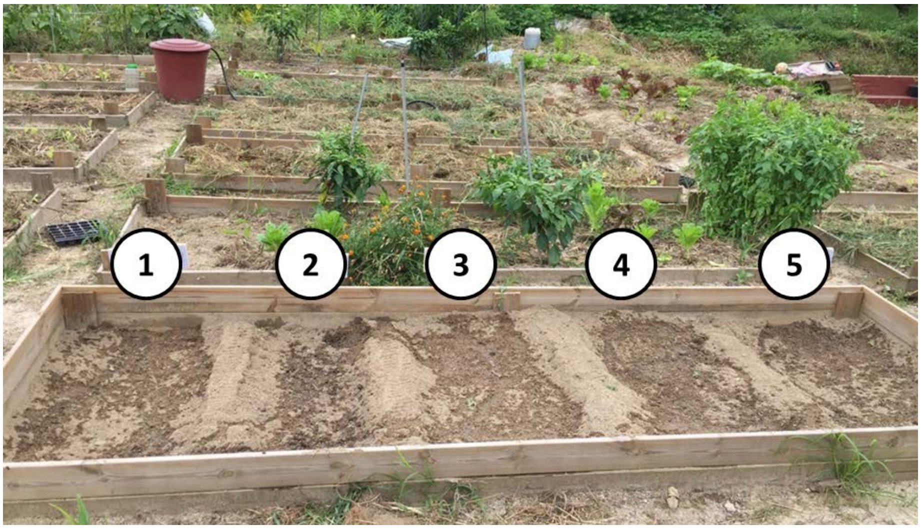

Figure 7.8. The Soil Sections for Cultivation

The seeds are planted in three rows and two columns with 25 cm vertical and 50 cm horizontal distance. The seeds are planted in 15 cm under the surface of the soil. Irrigation was done with available tap-water in the amount of 2.5 L/day for each section, equally.

7.2.3. Measurement Procedure

The characteristics of all soil samples were measured every three days. For this purpose, 1 g soil samples have been gathered carefully from the distance of 10 cm away from the plant root and 5 cm distance from the soil surface.

Organic matter content and macronutrient content (total phosphorus and nitrogen as total nitrogen, ammonia, and nitrate) have been measured as explained in chapters 4 and 5 for each soil samples in every three days interval. Also, in every ten days interval, pH and electrical conductivity (EC) has been measured using a Lee Valley Soil pH Meter, Model AB927 (Lee Valley Tools Ltd. Ogdensburg, New York, USA) and a Direct Soil EC Tester, Model HI98331 (Hanna Instruments, Inc., Woonsocket, Rhode Island, USA), respectively. Table 7.1 presents the initial characteristics of the soil samples.

Table 7.1. Initial Characteristics of Soil Treatment Samples

Soil Treatments	Total Nitrogen (mg/kg)	NH_4^+/NO_3^- Ratio	Total Phosphorus (mg/kg)	C/N Ratio	pH	Electrical Conductivity (ms/cm)
Intact Soil (Control)	3163	10.8	217	43.9	7.2	0.76
Fertilizer	4346	7.4	339	41.0	7.0	0.55
Urine	4542	7.5	368	29.5	8.1	2.58
Feces	4109	7.5	278	39.3	6.9	0.91
Mixture	4436	7.5	323	34.4	7.5	1.75

Also starting from the budding day in every ten days interval, the leaf area of the plan has been measured using a leaf area meter produced by LI-COR BioSciences, located in Omaha, Nebraska, USA. The weight and length of the plants have been measured after harvesting and analysis of variance (ANOVA), T-Test, F-Test, and Tukey Kramer Multiple Comparison Procedure has been applied to the obtained data. The harvesting procedure was done after 60 days before the full maturity of the plants because of the significant temperature drop.

The water content of the roots was determined gravimetrically using Method No. 1684 of US-EPA standards (USEPA 1979). Furthermore, the extracts of harvested plants were prepared, and the sugar content of them in degrees Brix was measured using a Digital Refractometer model PR-101α (ATAGO Co., LTD. Tokyo, Japan).

7.3. Results and Discussions

7.3.1. Nutrient Consumption

Figure 7.9 shows the concentration of total nitrogen in soil samples at each time interval. There is a notable gap between the intact soil with other treated ones. Among whole treated ones, urine has the highest amount of nutrients.

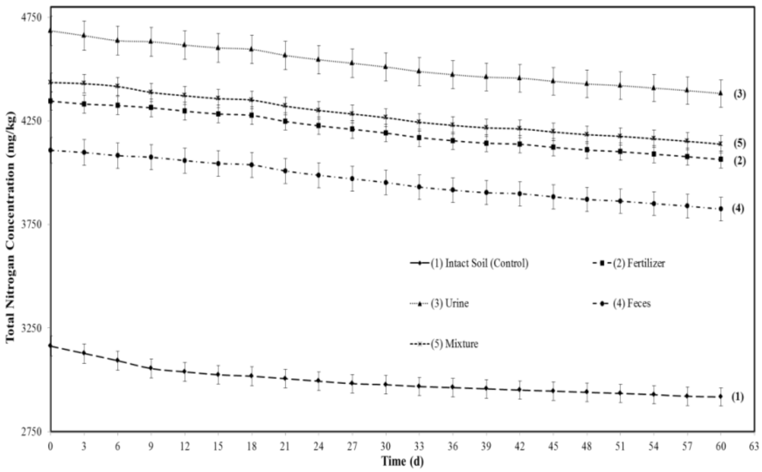

Figure 7.9. Changes in Total Nitrogen Concentration of Each Treated Soil Samples

From figures 7.9 it becomes clear that trend for nutrient consumption is not similar in all treatment cases. Figure 7.10, showing the differences of the final and initial amount of total nitrogen, illustrates that soil treated with urine is releasing nitrogen much faster than other samples.

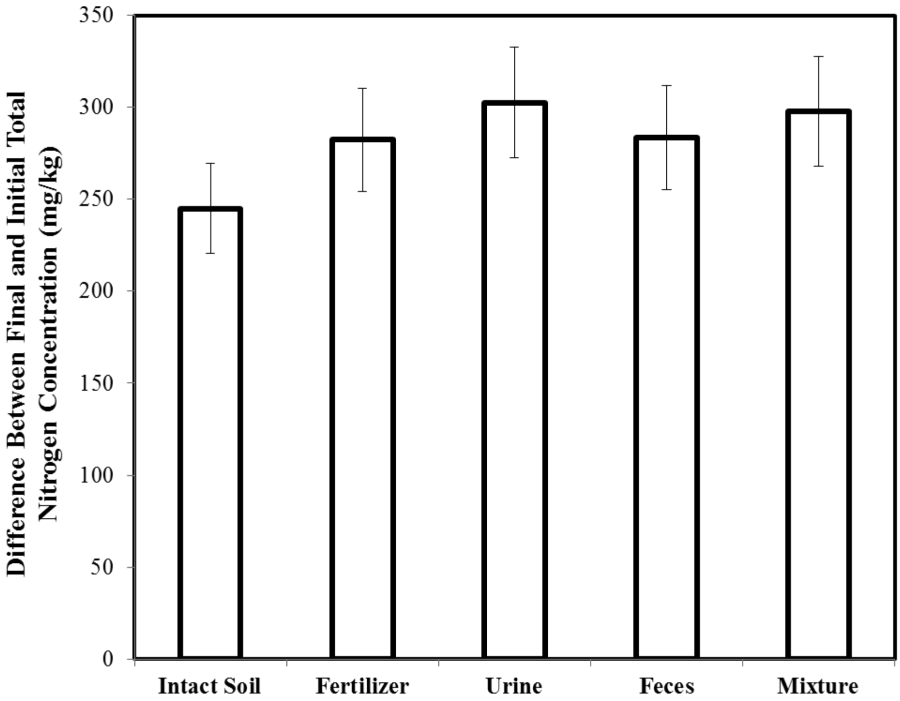

Figure 7.10. Difference between Final and Initial Total Nitrogen Concentration of Each Treated Soil Samples

This might be due to lower C/N ratio of the soil treated with urine. In this case, although urine has a higher amount of nitrogen, it can release it rapidly in comparison with other treated soils. This fact can be also explained by considering figures 7.11 and 7.12 which are illustrating the results of pH and EC measurement. Rapid release of nitrogen from soil treated with urine caused highest acidification and reduction in EC in comparison with other soil samples (Chrispim et al. 2017).

The soil treated with mixture of treated urine and treated feces compost has the most similar characteristics of the soil treated with commercial fertilizer. The same trend was observed for total phosphorus.

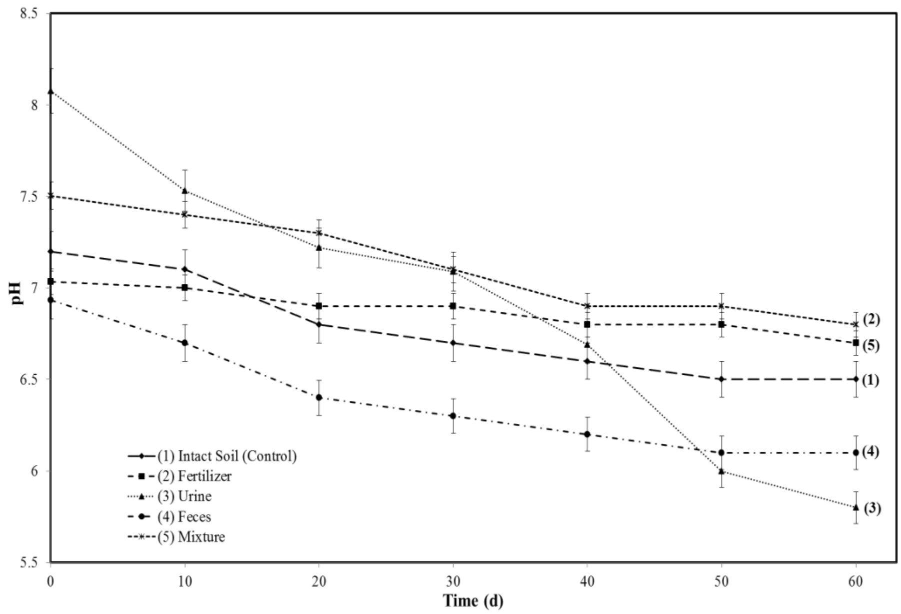

Figure 7.11. Changes in pH of Each Treated Soil Samples

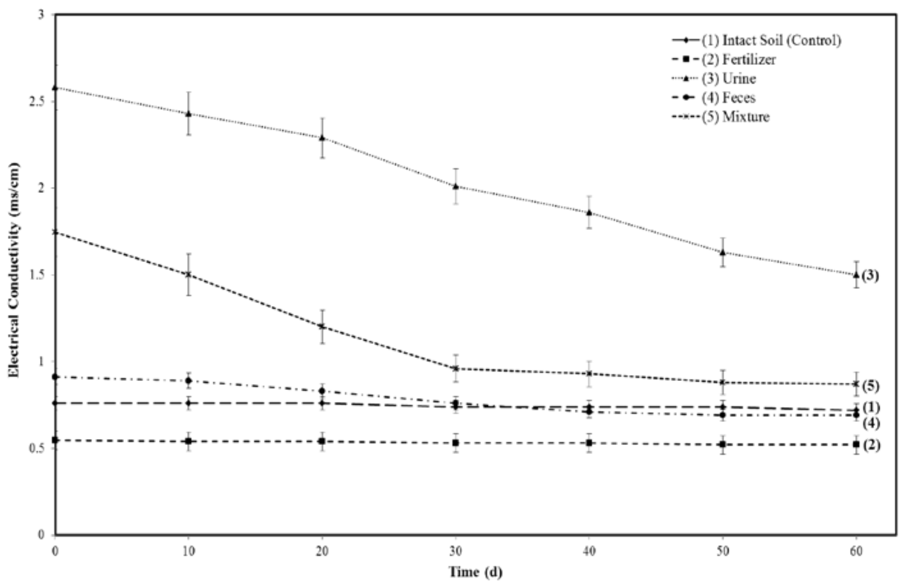

Figure 7.12. Changes in Electrical Conductivity of Each Treated Soil Samples

7.3.2. Leaf Size Growth

Figure 7.13 shows the leaf size growth of the white radish in each treated soil section.

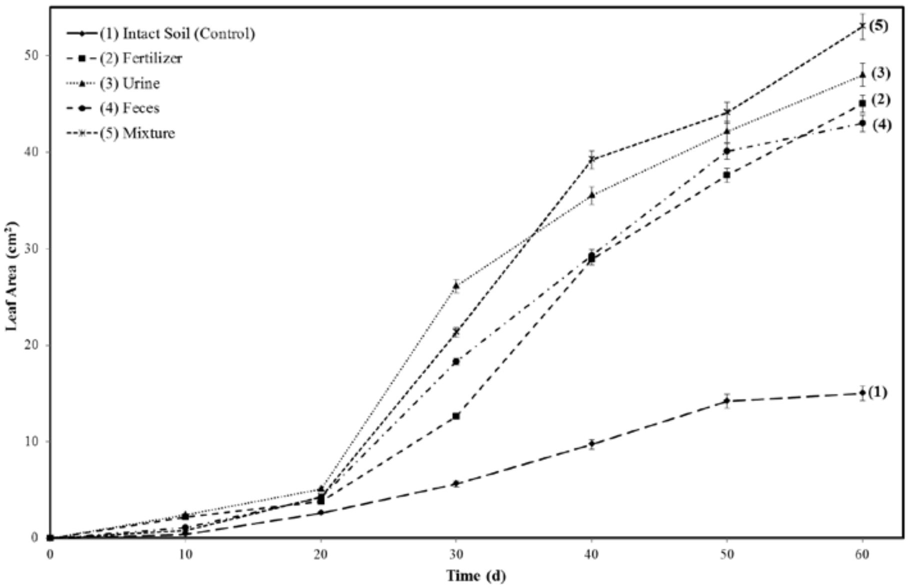

Figure 7.13. Leaf Size Growth of Plants in Soils with Different Treatments

In the beginning, the plants grown in the soil treated with urine shows a rapid trend in leaf growth which might be because of the faster release of nitrogen. However, later on, the leaves became yellow, and the growth trend became slower.

As presented in figure 7.14, at the time of harvesting, the soil treated with mixture of treated urine and treated feces compost has larger and greener leaves, even comparing with the soil treated with commercial fertilizer. This may be due to lower C/N ratio which gives a better release of nitrogen.

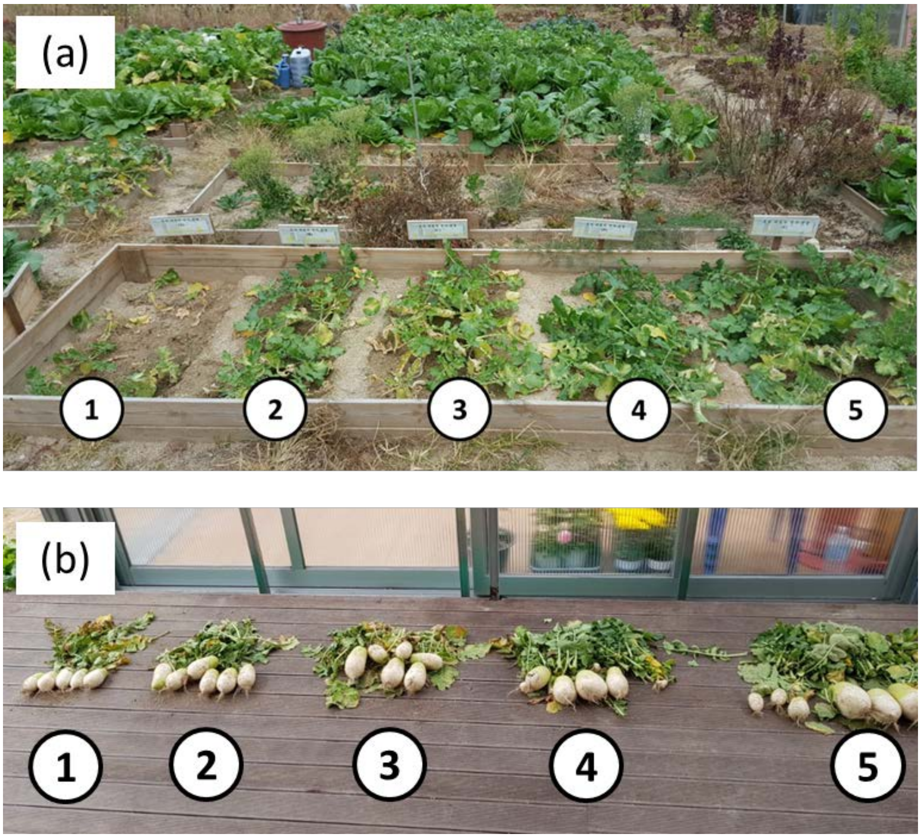

Figure 7.14. Condition of (a) Plants and (b) Roots at the Harvesting Day

It is noteworthy to mention that it is observed that the leaves of plants grown in the soil treated with urine have been eaten by insects because, in this study, we have not used any pesticides.

7.3.3. Root Growth

Sixty days after starting the experiments, harvesting process was executed. Figures 7.15, 7.16, and 7.17 illustrate the situation of root mass and length of the harvested plants.

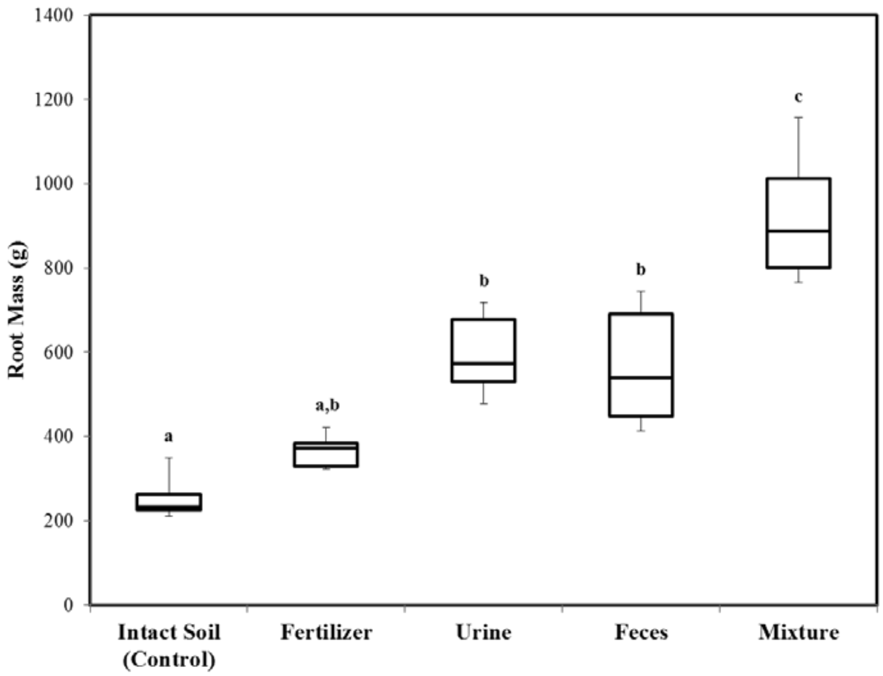

Figure 7.15. Comparison of Root Mass of Plants Grew in Different Soil Samples

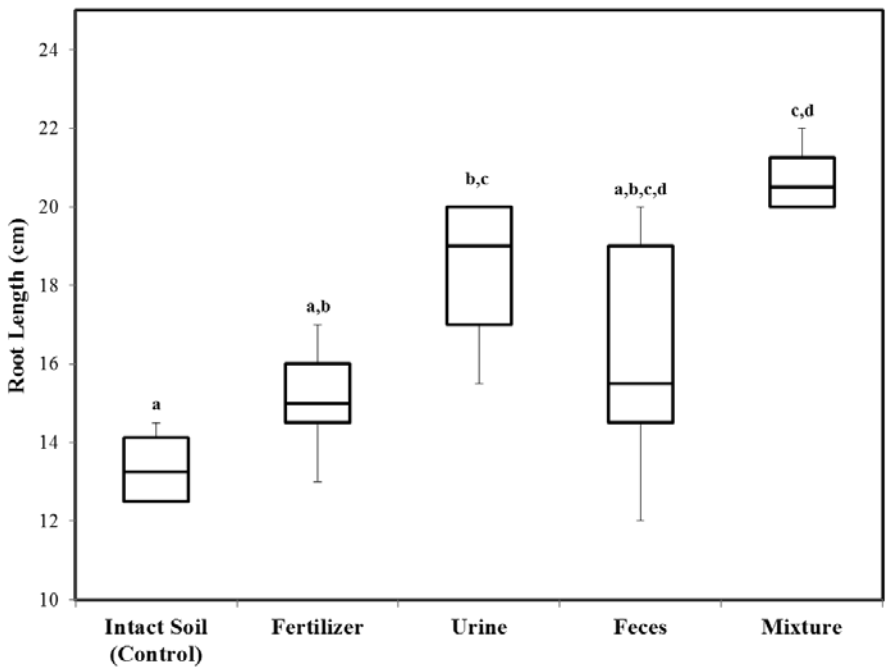

Figure 7.16. Comparison of Root Length of Plants Grew in Different Soil Samples

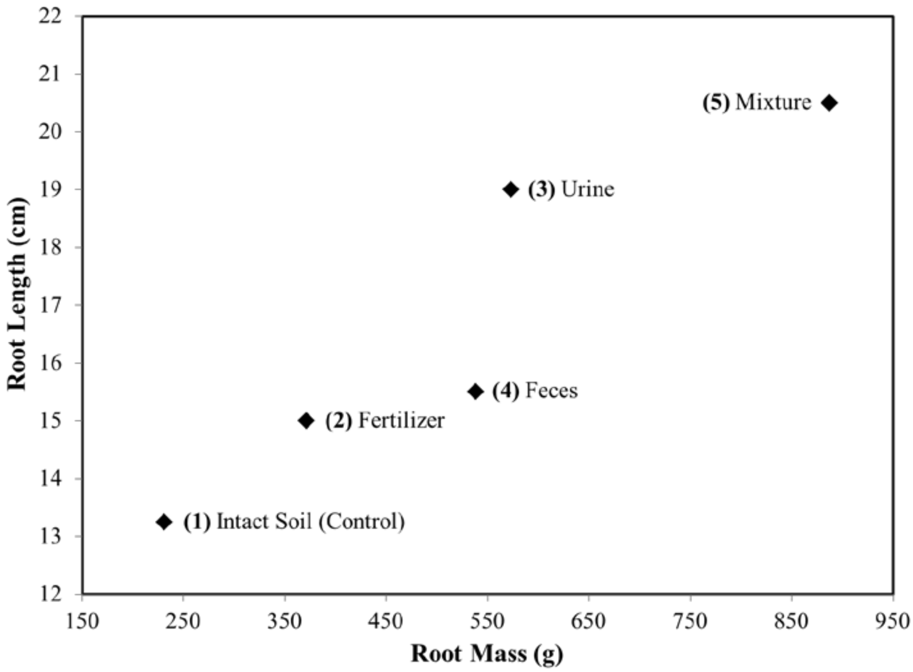

Figure 7.17. Comparison of Root Mass and Length of Plants Grew in Different Soil Samples

It became clear that plants which grew in soil samples treated with urine and the mixture of urine and feces have heavier and longer roots. Also as presented in figures 7.18 and 7.19, these samples contain the most amount of water and sugar compared with other plants.

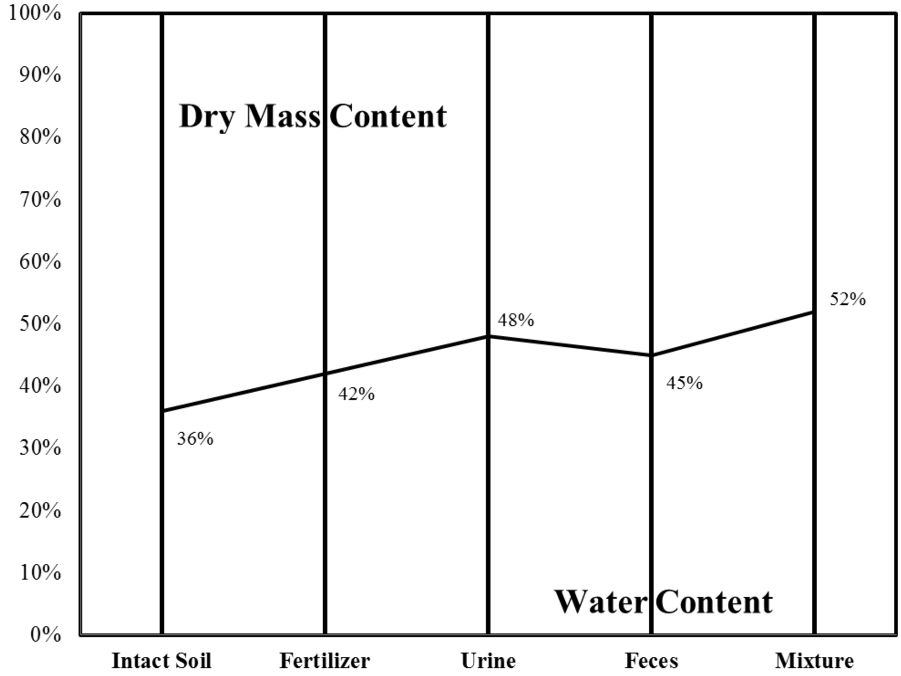

Figure 7.18. Comparison of Water Contents of Plants Grew in Different Soil Samples

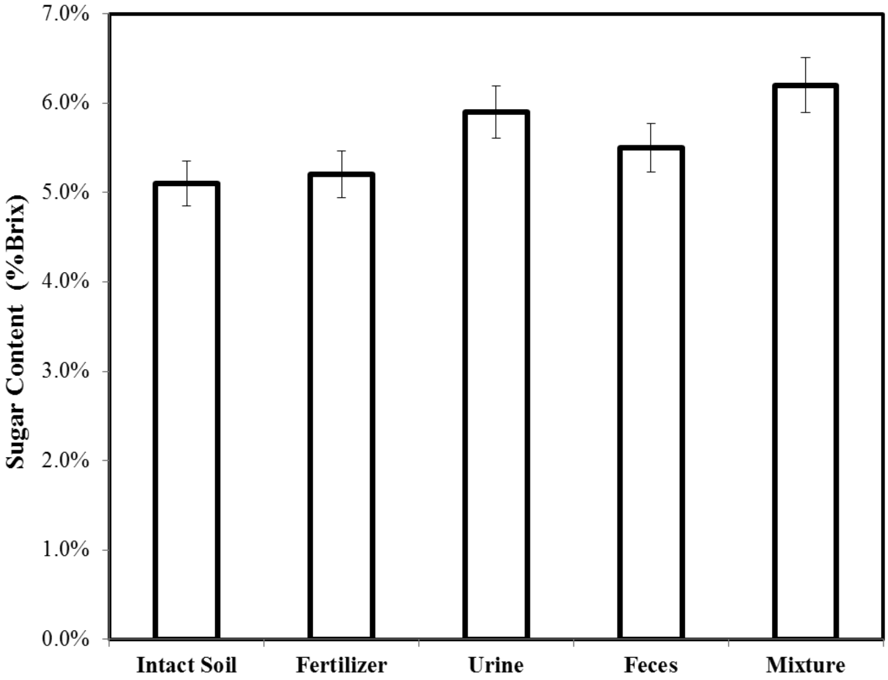

Figure 7.19. Comparison of Sugar Contents of Plants Grew in Different Soil Samples

These results yield that white radish cultivation using urine and mixture of urine and feces can be even more productive than applying commercial fertilizer.

7.4. Conclusions

In this study, the utilization of treated urine and feces as fertilizer has been examined through a field study of RCS system. Our results show that utilizing treated sanitary matters as fertilizer to grow white radish is quite comparable to using commercial fertilizer. The results of this study, not only supports the improvement of plant growth, but also, shows that utilizing treated sanitary matters in an RCS system as a fertilizer can potentially make an impact on grand challenges such as access to sanitation and fertilizer, both of which lie in the agriculture, water, and food nexus.

Treated sanitary matters from RCS systems are ubiquitous and low-cost, safely collecting and usable as fertilizer. An extensive and bright public knowledge about these facts can increase the number of people with access to adequate fertilizers and well as the social acceptability of RCS systems. Thus it can be a very good motivation in providing RCS systems in areas with low sanitation coverage.

8. Conclusions and Recommendations

8.1. Conclusions

In this study, we discussed global sanitation problems. To solve these problems, global solution goals and guidelines are given through defining MDG 7, which continued in more detailed though SDG 6. Solutions toward SDG 6 should be sustainable to ensure the access to sanitation for all. A historical review through the development of sanitation shows that a new paradigm for sanitation is required toward SDG 6 which consumes no or less water and energy, separates urine from feces, utilizes the separately treated sanitary matters as fertilizer, and is safe and secure to use as well as having a sustainable maintenance process.

Following the principles mentioned above, resource circulated sanitation (RCS) systems are defined. In such systems, urine and feces treatment should be through a safe and sound process. Thus the maintenance should be well managed. Table 8.1 presents the comparison between RCS systems with WOS and ROS systems.

Table 8.1. Comparison of Different Sanitation Options

Sanitation Options	Water Consumption	Energy Consumption	Source Separation	Onsite Utilization	Easy Maintenance
WOS	Very High		X	X	It Clogs (X)
ROS	Very Low		O	X	It Smells (X)
RCS				O	All Okay (O)

Accordingly, in this dissertation, innovative biological treatment methods are introduced for both urine and feces to make them meet the standard criteria for fertilizers.

Our research showed that the optimum concentration of bio-seed (6×10^5 *N. europaea* cells L^{-1}) that not only leads to the least nutrient loss but also results in an adequate nitrate:ammonium ratio and regulates the amount of nitrate produced, thereby preventing over-fertilization, was determined. Furthermore, adding 7000–8000 or more *N. Europaea* cells, along with 10,000 *N. Winogradskyi* cells, to 1 g feces, resulted in up to 90% degradation of the organic matter by enhancing the growth of heterotrophic microorganisms. Moreover, the nitrogen composition and pH of the degraded feces were optimized to meet the criteria for standard fertilizer.

In the case of utilizing urine, to avoid the challenges of using liquid fertilizers, nutrients can be harvested and be utilized in solid form. Our studies show that the addition of solid additives such as powdered rice straw can help with harvesting nutrients from urine. Investigating the procedure and efficiency of using powdered rice straw for nutrient harvesting by tracking the reductions in ammonia, phosphate, magnesium, and calcium ions showed that the ammonia, phosphate, and magnesium ions showed similar reduction trends. However, the reduction process was limited by the magnesium and phosphate availability, which reduced the nutrient harvesting efficiency.

For the case of providing a sustainable maintenance for RCS systems, the significant challenges are identified to be the urine scale formation and urine odor. The former leads to clogging the pipelines of the system and the latter causes increasing the water consumption for the maintenance purposes. Some meaningful solutions for managing and solving urine scale problems have been suggested. In particular, the results show that mixing urine with seawater or high salinity groundwater will increase the potential for urine scale formation by increasing total dissolved solids (TDS) and pH. However, using rainwater for urinal flushing can significantly reduce the TDS and pH.

Using the standard threshold odor number (TON) measurement as an indicator of urine odor, the effects of the pH and temperature of the diluting water regarding the amount of water:urine dilution ratio were studied. Investigating the effects of temperature and pH of the diluting water on TON when the dilution ratio was constant shows that lowering the pH and temperature of the diluting water can reduce the minimum dilution ratio needed to achieve TON = 0. At constant dilution ratio, reducing pH seemed to be more efficient, sustainable, and economical in comparison to adjusting the temperature of the diluting water. It was found that, based on the specific pH and temperature of the diluting water, there is a minimum dilution ratio required to avoid urine odor.

Based on our findings, we have designed an RCS system called *TORRY* and installed in an urban farming center to investigate its efficiency. The produced fertilizer derived from *TORRY* have been examined and compared with application of a local commercial fertilizer to cultivate white radish. The results show that utilizing treated sanitary matters can be an excellent alternative for commercial fertilizers. Such results can be useful in attracting public attention to the advantages of RCS systems which can improve its acceptability.

8.2.Key Recommendations

Based on the results of this dissertation, challenges of RCS systems can be addressed scientifically to improve their efficiency.

Applying the optimum nitrifying bio-seed dosage results in not only a nitrate:ammonium ratio of about 1:1 and higher efficiency of cultivating ornamental plants such as I. nil but also the lowest nitrogen loss and least stabilization time; this prevents over-fertilization and eliminates the need for dilution or dewatering, thereby lowering water and energy consumption. Another advantage of using this optimum concentration of bio-seed is that further application of inorganic chemical additives is not required.

The nutrients harvested from source separated urine by rice straw were identified to be mostly struvite. Balancing the phosphate and magnesium ions with ammonia is recommended to improve the efficiency of nutrient harvesting. The treated powdered rice straw can serve as an excellent solid fertilizer, while the remaining urine, which includes fewer nutrients, can be utilized for irrigation or sent to wastewater treatment plants.

Our approach for treating source-separated feces could be useful for managing RCS systems by the specific aims of such systems, i.e., reducing feces volume by bio-degradation and increasing the fertility to meet the standard criteria for fertilizer as well as removing pathogens for implementation in safe practices. From the conducted studies, we may hypothesize that by supplying of some critical microbial growth promoters, such as amino acids and vitamins, the nitrifying bacteria will be competitive in organic-rich wastes such that their metabolism will affect the overall chemistry of the wastes during incubation. Such approach can be a very unique topic for further studies. Although RCS systems have advantages even comparing with ROS systems, there are challenges which should be addressed in further studies. Some of these challenges are listed below which all are being considered for our upcoming research.

One significant challenge is the type of reactors for both urine and feces treatment. Optimizing the type of reactors will provide an excellent chance for scaling up the RCS systems. A study on the comparison of different types of reactors, including batch, CSTR, and PFR for the behavior of urine and feces is recommended. Further studies should be done for harvesting nutrients from using other types of solid additives.

As for the feces treatment, a new approach for designing reactor is required. The basic of this innovative reactor should be not to mix formerly treated feces with the new ones to improve the pathogen removal efficiency. The application of sanitary matters as fertilizer should be considered for a broader range in the type of the plants. We think that it might be possible to optimize the characteristics of the fertilizers for any specific types of plants.

The economic concepts of RCS should be considered. For any specific RCS projects, a life-cycle assessment should be done for optimizing the design of the system. Development in the construction of RCS systems following the opinion and culture of the end-users are critical. Further scientific studies should be done on the social concepts of RCS through statistical methods, and the public knowledge should be improved by considering related education programs.

Bibliography

Aiello, A. E., Larson, E. L. and Sedlak, R. (2008) Against disease: Impact of hygiene and cleanliness on health. *American journal of infection control, 36*(10 Suppl), pp. S109-S109.

Antonini, S., Nguyen, P. T., Arnold, U., Eichert, T. and Clemens, J. (2012) Solar thermal evaporation of human urine for nitrogen and phosphorus recovery in Vietnam. *Science of the Total Environment, 414*, pp. 592-599.

APHA/AWWA/WEF (2012) *Standard Methods for the Examination of Water and Wastewater*, 22 ed., Washington, D.C.: American Public Health Association.

Ashbolt, N. J. (2004) Microbial contamination of drinking water and disease outcomes in developing regions. *Toxicology, 198*(1), pp. 229-238.

Ban, Z. and Dave, G. (2004) Laboratory studies on recovery of N and P from human urine through struvite crystallisation and zeolite adsorption. *Environmental technology, 25*(1), pp. 111-121.

Beal, C., Gardner, T., Ahmed, W., Walton, C. and Hamlyn-Harris, D. (2008) Urine-separation and reuse trials. *Water: Journal of the Australian Water Association, 35*(1), pp. 66-69.

Beler-Baykal, B., Bayram, S., Akkaymak, E. and Cinar, S. (2004) Removal of ammonium from human urine through ion exchange with clinoptilolite and its recovery for further reuse. *Water Science and Technology*, *50*(6), pp. 149-156.

Berndtsson, J. C. (2006) Experiences from the implementation of a urine separation system: Goals, planning, reality. *Building and environment, 41*(4), pp. 427-437.

Bond, T., Roma, E., Foxon, K., Templeton, M. and Buckley, C. (2013) Ancient water and sanitation systems–applicability for the contemporary urban developing world. *Water Science and Technology*, *67*(5), pp. 935-941.

Bongartz, P., Musyoki, S. M., Milligan, A. and Ashley, H. (2010) Tales of shit: Community-Led Total Sanitation in Africa–an overview. *Tales of shit: Community-Led Total Sanitation in Africa*, pp. 27.

Bracken, P., Wachtler, A., Panesar, A. and Lange, J. (2007) The road not taken: how traditional excreta and greywater management may point the way to a sustainable future. *Water Science and Technology: Water Supply, 7*(1), pp. 219-227.

Chain, P., Lamerdin, J., Larimer, F., Regala, W., Lao, V., Land, M., Hauser, L., Hooper, A., Klotz, M. and Norton, J. (2003) Complete genome sequence of the ammonia-oxidizing bacterium and obligate chemolithoautotroph Nitrosomonas europaea. *Journal of bacteriology, 185*(9), pp. 2759-2773.

Chau, K. (1993) Management of limited water resources in Hong Kong. *International Journal of Water Resources Development, 9*(1), pp. 65-73.

Chrispim, M. C., Tarpeh, W. A., Salinas, D. T. and Nolasco, M. A. (2017) The sanitation and urban agriculture nexus: urine collection and application as fertilizer in São Paulo, Brazil. *Journal of Water Sanitation and Hygiene for Development, 7*(3), pp. 455-465.

Dao, A.-D., Nguyen, V.-A. and Han, M. (2013) Benefit of the drinking water supply system in office building by rainwater harvesting: a demo project in Hanoi, Vietnam. *Environmental Engineering Research, 18*(2), pp. 103-108.

Decrey, L., Udert, K. M., Tilley, E., Pecson, B. M. and Kohn, T. (2011) Fate of the pathogen indicators phage ΦX174 and Ascaris suum eggs during the production of struvite fertilizer from source-separated urine. *Water Research, 45*(16), pp. 4960-4972.

Dodd, M. C., Zuleeg, S., Gunten, U. v. and Pronk, W. (2008) Ozonation of source-separated urine for resource recovery and waste minimization: process modeling, reaction chemistry, and operational considerations. *Environmental Science & Technology, 42*(24), pp. 9329-9337.

Drangert, J.-O. (1998) Urine blindness and the use of nutrients from human excreta in urban agriculture. *GeoJournal, 45*(3), pp. 201-208.

Esray, S. A. (2001) Towards a recycling society: ecological sanitation-closing the loop to food security. *Water Science and Technology, 43*(4), pp. 177-187.

Esrey, S. A., Andersson, I., Hillers, A. and Sawyer, R. (2001) *Closing the loop: ecological sanitation for food security*.

Etter, B., Tilley, E., Khadka, R. and Udert, K. (2011) Low-cost struvite production using source-separated urine in Nepal. *Water Research, 45*(2), pp. 852-862.

European Commission (2003) Regulation (EC) No 2003/2003 of the European Parliament and of the Council of 13 October 2003 relating to fertilizers. *European Parliament and European Council*.

Fleisher, G. R. and Ludwig, S. (2010) *Textbook of pediatric emergency medicine,* Lippincott Williams & Wilkins.

Ganesapillai, M., Simha, P. and Zabaniotou, A. (2015) Closed-loop fertility cycle: Realizing sustainability in sanitation and agricultural production through the design and implementation of nutrient recovery systems for human urine. *Sustainable production and consumption, 4,* pp. 36-46.

Ganrot, Z., Dave, G. and Nilsson, E. (2007) Recovery of N and P from human urine by freezing, struvite precipitation and adsorption to zeolite and active carbon. *Bioresource Technology, 98*(16), pp. 3112-3121.

Grady Jr, C. L., Daigger, G. T., Love, N. G. and Filipe, C. D. (2011) *Biological wastewater treatment,* Boca Raton: CRC press.

Gunun, P., Wanapat, M. and Anantasook, N. (2013) Effects of physical form and urea treatment of rice straw on rumen fermentation, microbial protein synthesis and nutrient digestibility in dairy steers. *Asian-Australasian journal of animal sciences, 26*(12), pp. 1689.

Guzha, E., Nhapi, I. and Rockstrom, J. (2005) An assessment of the effect of human faeces and urine on maize production and water productivity. *Physics and Chemistry of the Earth, Parts A/B/C, 30*(11), pp. 840-845.

Han, M. and Hashemi, S. (2017) Sanitation Revolution: From Waste to Resource. *Desalination and Water Treatment*, *91*, pp. 305-310. doi: 10.5004/dwt.2017.20605.

Han, M., Hashemi, S., Joo, S. H. and Kim, T. (2016) Novel integrated systems for controlling and prevention of mosquito-borne diseases caused by poor sanitation and improper water management. *Journal of Environmental Chemical Engineering*, *4*(4), pp. 3718-3723. doi: 10.1016/j.jece.2016.08.013.

Han, M. and Kim, M. (2014) Revisiting the technical and social aspects of wastewater management in ancient Korea. in Angelakis, A. N. and Rose, J. B., (eds.) *Evolution of Sanitation and Wastewater Technologies through the Centuries,*London: IWA Publishing. pp. 301-312.

Han, M. and Mun, J. (2011) Operational data of the Star City rainwater harvesting system and its role as a climate change adaptation and a social influence. *Water Science and Technology*, *63*(12), pp. 2796-2801.

Hannan, C. and Andersson, I. (2001) *Gender perspective on Ecological Sanitation*, Available: http://www.ecosanres.org/PDF%20files/Nanning%20PDFs/ENG/Hannan%20%20Andersson.pdf.

Hashemi, S. (2015) *Fate of Nitrogen in Urine Separated Toilet Systems*. Unpublished M. Sc. Thesis, Seoul National University, Seoul.

Hashemi, S. and Han, M. (2017a) Control of urine odor in different sanitation practices and its implication on water saving. *Journal of Water Sanitation and Hygiene for Development*, *7*(1), pp. 156-162. doi: 10.2166/washdev.2017.094.

Hashemi, S. and Han, M. (2017b) Effect of Nitrosomonas europaea Bio-Seed Addition on the Fate of Carbon and Nitrogen Compounds in Human Feces. *Waste and Biomass Valorization, In Press*. doi: 10.1007/s12649-017-9857-5.

Hashemi, S. and Han, M. (2017c) Harvesting Nutrients from Source-Separated Urine Using Powdered Rice Straw. *Environmental Technology*, *In Press*. doi: 10.1080/09593330.2017.1321690.

Hashemi, S. and Han, M. (2017d) Methods for controlling stored urine odor in resource-oriented sanitation. *Journal of Water Sanitation and Hygiene for Development*, *7*(3), pp. 507-514. doi: 10.2166/washdev.2017.098.

Hashemi, S. and Han, M. (2018) Optimizing source-separated feces degradation and fertility using nitrifying microorganisms. *Journal of Environmental Management*, *206*, pp. 540-546. doi: 10.1016/j.jenvman.2017.10.074.

Hashemi, S., Han, M. and Kim, T. (2015a) The effect of material and flushing water type on urine scale formation. *Water Science and Technology*, *72*(11), pp. 2027-33. doi: 10.2166/wst.2015.422.

Hashemi, S., Han, M. and Kim, T. (2015b) Identification of urine scale problems in urinals and the solution using rainwater. *Journal of Water Sanitation and Hygiene for Development*, *5*(2), pp. 322-329. doi: 10.2166/washdev.2015.100.

Hashemi, S., Han, M. and Kim, T. (2016) Optimization of fertilization characteristics of urine by addition of Nitrosomonas europaea bio-seed. *Journal of the Science of Food and Agriculture*, *96*(13), pp. 4416-22. doi: 10.1002/jsfa.7652.

Hashemi, S., Han, M., Kim, T. and Kim, Y. (2015c) Innovative toilet technologies for smart and green cities. in *Proceedings of the 8th Conference of the International Forum on Urbanism, 22–24 June 2015*. pp. 873-879. doi: 10.3390/ifou-E013.

Hashemi, S., Han, M. and Namkung, E. (2018) Fate of Fecal Indicators in Resource-Oriented Sanitation Systems Using Nitrifying Bio-Treatment. *International Journal of Environmental Research and Public Health*, *15*(1), 164. doi: 10.3390/ijerph15010164.

Heinonen-Tanski, H., Sjöblom, A., Fabritius, H. and Karinen, P. (2007) Pure human urine is a good fertiliser for cucumbers. *Bioresource Technology*, *98*(1), pp. 214-217.

Heinonen-Tanski, H. and van Wijk-Sijbesma, C. (2005) Human excreta for plant production. *Bioresource Technology*, *96*(4), pp. 403-411.

Höglund, C. (2001) *Evaluation of microbial health risks associated with the reuse of source-separated humna urine*. Unpublished Doctoral thesis, comprehensive summary, Bioteknologi, Stockholm.

Höglund, C., Ashbolt, N., Stenström, T. A. and Svensson, L. (2002) Viral persistence in source-separated human urine. *Advances in Environmental Research, 6*(3), pp. 265-275.

Höglund, C., Vinnerås, B., Stenström, T. and Jönsson, H. (2000) Variation of chemical and microbial parameters in collection and storage tanks for source separated human urine. *Journal of Environmental Science & Health Part A, 35*(8), pp. 1463-1475.

Hommes, N. G., Sayavedra-Soto, L. A. and Arp, D. J. (2003) Chemolithoorganotrophic growth of Nitrosomonas europaea on fructose. *Journal of bacteriology, 185*(23), pp. 6809-6814.

Hoyt, E. (1972) Hygiene in Ancient China. *CHEST Journal, 61*(2), pp. 133-133.

Hu, M., Fan, B., Wang, H., Qu, B. and Zhu, S. (2016) Constructing the ecological sanitation: a review on technology and methods. *Journal of Cleaner Production, 125*, pp. 1-21.

Ishii, S. K. and Boyer, T. H. (2015) Life cycle comparison of centralized wastewater treatment and urine source separation with struvite precipitation: focus on urine nutrient management. *Water Research, 79*, pp. 88-103.

Jack, L. (2000) Overview of investigations addressing the issue of low water use sanitary appliances and associated drainage network design. *Building Services Engineering Research and Technology, 21*(2), pp. 139-144.

Jewitt, S. (2011) Poo gurus? Researching the threats and opportunities presented by human waste. *Applied Geography, 31*(2), pp. 761-769.

Jönsson, H. (2002) Urine separating sewage systems-environmental effects and resource usage. *Water Science and Technology, 46*(6-7), pp. 333-340.

Jönsson, H., Stintzing, A. R., Vinnerås, B. and Salomon, E. (2004) *Guidelines on the use of urine and faeces in crop production*, EcoSanRes Programme.

Karadagli, F., McAvoy, D. C. and Rittmann, B. E. (2009) Development of a mathematical model for physical disintegration of flushable consumer products in wastewater systems. *Water Environment Research, 81*(5), pp. 459-465.

Kemacheevakul, P., Polprasert, C. and Shimizu, Y. (2011) Phosphorus recovery from human urine and anaerobically treated wastewater through pH adjustment and chemical precipitation. *Environmental technology*, *32*(7), pp. 693-698.

Kim, Y., Hashemi, S., Han, M., Kim, T. and Sohn, H. G. (2016) The Waterless Portable Private Toilet: An Innovative Sanitation Solution in Disaster Zones. *Disaster Medicine and Public Health Preparedness*, *10*(2), pp. 281-5. doi: 10.1017/dmp.2015.166.

Kirchmann, H. and Pettersson, S. (1994) Human urine-chemical composition and fertilizer use efficiency. *Nutrient Cycling in Agroecosystems*, *40*(2), pp. 149-154.

Krümmel, A. and Harms, H. (1982) Effect of organic matter on growth and cell yield of ammonia-oxidizing bacteria. *Archives of Microbiology*, *133*(1), pp. 50-54.

Kujawa-Roeleveld, K. and Zeeman, G. (2006) Anaerobic treatment in decentralised and source-separation-based sanitation concepts. *Reviews in Environmental Science and Bio/Technology*, *5*(1), pp. 115-139.

La Berge, A. E. F. (2002) *Mission and method: the early nineteenth-century french public health movement*, Cambridge University Press.

Laanbroek, H. J. and Gerards, S. (1993) Competition for limiting amounts of oxygen between Nitrosomonas europaea and Nitrobacter winogradskyi grown in mixed continuous cultures. *Archives of Microbiology*, *159*(5), pp. 453-459.

Langergraber, G. and Muellegger, E. (2005) Ecological Sanitation—a way to solve global sanitation problems? *Environment international, 31*(3), pp. 433-444.

Larsen, T. A., Lienert, J., Joss, A. and Siegrist, H. (2004) How to avoid pharmaceuticals in the aquatic environment. *Journal of Biotechnology, 113*(1), pp. 295-304.

Larsen, T. A., Peters, I., Alder, A., Eggen, R., Maurer, M. and Muncke, J. (2001) Re-engineering the toilet for sustainable wastewater management. *Environmental Science & Technology, 35*(9), pp. 192A-197A.

Larsson, D. J., de Pedro, C. and Paxeus, N. (2007) Effluent from drug manufactures contains extremely high levels of pharmaceuticals. *Journal of hazardous materials, 148*(3), pp. 751-755.

Leejeerajumnean, A., Ames, J. and Owens, J. (2000) Effect of ammonia on the growth of Bacillus species and some other bacteria. *Letters in applied microbiology, 30*(5), pp. 385-389.

Lens, P., Lettinga, G. and Vallero, M. (2004) Environmental protection technologies for sustainable development. in *Enhancing urban environment by environmental upgrading and restoration*: Springer. pp. 341-349.

Lind, B.-B., Ban, Z. and Bydén, S. (2000) Nutrient recovery from human urine by struvite crystallization with ammonia adsorption on zeolite and wollastonite. *Bioresource Technology, 73*(2), pp. 169-174.

Littlewood, K. and Butler, D. (2003) Movement mechanisms of gross solids in intermittent flow. *Water Science and Technology, 47*(4), pp. 45-50.

Lu, J. (2017) *India's 'successful' toilet campaign may be missing its mark*, Available: http://www.humanosphere.org/basics/2017/05/indias-successful-toilet-campaign-may-missing-mark/ [Accessed December 22 2017].

Mattelaer, J. J. (1999) Some historical aspects of urinals and urine receptacles. *World journal of urology, 17*(3), pp. 145-150.

Maurer, M., Pronk, W. and Larsen, T. (2006) Treatment processes for source-separated urine. *Water Research, 40*(17), pp. 3151-3166.

McDougall, J. and Swaffield, J. (2000) Simulation of building drainage system operation under water conservation design criteria. *Building Services Engineering Research and Technology, 21*(1), pp. 41-51.

McDougall, J. and Swaffield, J. (2007) Transport of deformable solids within building drainage networks. *Building Research and Information, 35*(2), pp. 220-232.

Menter, U. (2016) *New sanitation techniques in the development cooperation: An economical reflection,* BoD–Books on Demand.

Moe, C. L. and Rheingans, R. D. (2006) Global challenges in water, sanitation and health. *Journal of water and health, 4*(S1), pp. 41-57.

Münch, E. v., Schöpe, A. and Rüd, S. (2009) Ecosan–recycling oriented wastewater management and sanitation systems GTZ. *URL: www. gtz. de/ecosan.*

Münch, E. v. and Winker, M. (2009) Technology Review| Urine diversion components. *Overview of urine diversion components such as waterless urinals, urine diversion toilets, urine storage and reuse systems. Sustainable sanitation–ecosan program. Eschborn*.

Needham, J. and Lu, G.-D. (1959) Hygiene and Preventive Medicine in Ancient China. *Health Education Journal, 17*(3), pp. 170-179.

Nyberg, K. A., Ottoson, J. R., Vinnerås, B. and Albihn, A. (2014) Fate and survival of Salmonella Typhimurium and Escherichia coli O157: H7 in repacked soil lysimeters after application of cattle slurry and human urine. *Journal of the science of food and agriculture, 94*(12), pp. 2541-2546.

O'Neal, J. A. and Boyer, T. H. (2013) Phosphate recovery using hybrid anion exchange: Applications to source-separated urine and combined wastewater streams. *Water Research, 47*(14), pp. 5003-5017.

Okem, A., Xulu, S., Tilley, E., Buckley, C. and Roma, E. (2013) Assessing perceptions and willingness to use urine in agriculture: A case study from rural areas of eThekwini Municipality, South Africa. *Journal of Water Sanitation and Hygiene for Development, 3*(4), pp. 582-591.

Ørskov, E. (1994) Recent advances in understanding of microbial transformation in ruminants. *Livestock production science, 39*(1), pp. 53-60.

Ørskov, E. (1998) Feed evaluation with emphasis on fibrous roughages and fluctuating supply of nutrients: a review. *Small Ruminant Research, 28*(1), pp. 1-8.

Platzer, C., Hoffmann, H. and Ticona, E. (2008) Alternatives to Waterborne Sanitation–a Comparative Study–Limits and Potentials. in: IRC Symposium: Sanitation for the Urban Poor.

Pradhan, S. K., Nerg, A.-M., Sjöblom, A., Holopainen, J. K. and Heinonen-Tanski, H. (2007) Use of human urine fertilizer in cultivation of cabbage (Brassica oleracea)—impacts on chemical, microbial, and flavor quality. *Journal of agricultural and food chemistry, 55*(21), pp. 8657-8663.

Pronk, W. and Kone, D. (2009) Options for urine treatment in developing countries. *Desalination, 248*(1-3), pp. 360-368.

Rehman, M. S. U., Rashid, N., Ashfaq, M., Saif, A., Ahmad, N. and Han, J.-I. (2015) Global risk of pharmaceutical contamination from highly populated developing countries. *Chemosphere, 138*, pp. 1045-1055.

Rieck, C., Von Münch, E. and Hoffmann, H. (2012) Technology Review of Urine-diverting dry toilets (UDDTs): Overview of design, operation, management and costs. *Deutsche Gesellschaft fuer Internationale Zusammenarbeit (GIZ) GmbH, Eschborn, Germany*.

Ronteltap, M., Maurer, M. and Gujer, W. (2007) Struvite precipitation thermodynamics in source-separated urine. *Water Research, 41*(5), pp. 977-984.

Rossi, L., Lienert, J. and Larsen, T. (2009) Real-life efficiency of urine source separation. *Journal of Environmental Management, 90*(5), pp. 1909-1917.

Sarnklong, C., Cone, J., Pellikaan, W. and Hendriks, W. (2010) Utilization of rice straw and different treatments to improve its feed value for ruminants: a review. *Asian-Australasian journal of animal sciences, 23*(5), pp. 680.

Savci, S. (2012) An agricultural pollutant: chemical fertilizer. *International Journal of Environmental Science and Development, 3*(1), pp. 73.

Schönning, C., Leeming, R. and Stenström, T. A. (2002) Faecal contamination of source-separated human urine based on the content of faecal sterols. *Water Research, 36*(8), pp. 1965-1972.

Schönning, C. and Stenström, T. (2004) Guidelines for the safe use of urine and faeces in. *Lübeck, Almanya in Ecological Sanitation Systems, EcoSanRes Programme & Stokholm Environment Institute, İsviçre*.

Shier, D., Butler, J. and Lewis, R. (2016) *Hole's Human Anatomy & Physiology,* 14 ed., New York: McGraw-Hill College.

Shuaeb, M. A. M. and Han, M. (2018) Clogging potential of low-flush toilet branch drain system. *Urban Water Journal, 15*(1), pp. 68-74. doi: 10.1080/1573062X.2017.1395898.

Sikora, L. and Stott, D. (1996) Soil organic carbon and nitrogen. in Doran, J. and Jones, A., (eds.) *Methods for Assessing Soil Quality*,Madison: Soil Science Society of America Special Publication. pp. 157-167.

Simha, P. and Ganesapillai, M. (2017) Ecological Sanitation and nutrient recovery from human urine: How far have we come? A review. *Sustainable Environment Research, 27*(3), pp. 107-116.

Starkl, M., Brunner, N., Feil, M. and Hauser, A. (2015) Ensuring Sustainability of Non-Networked Sanitation Technologies: An Approach to Standardization. *Environmental Science & Technology, 49*(11), pp. 6411-6418.

Sundin, K. A., Leeming, R. L. and Stenström, T. A. B. (1999) Degradation of faecal sterols in urine for assessment of faecal cross-contamination in source-separated human urine and urine storage tank sediment. *Water Research, 33*(9), pp. 1975-1980.

Texier, A.-C., Zepeda, A., Gómez, J. and Cuervo-López, F. (2012) Simultaneous elimination of carbon and nitrogen compounds of petrochemical effluents by nitrification and denitrification. in Patel, V., (ed.) *Petrochemicals*,Rijeka: InTech. pp. 101-134.

Tidåker, P., Sjöberg, C. and Jönsson, H. (2007) Local recycling of plant nutrients from small-scale wastewater systems to farmland—A Swedish scenario study. *Resources, Conservation and Recycling, 49*(4), pp. 388-405.

Tilley, E., Ulrich, L., Lüthi, C., Reymond, P., Schertenleib, R. and Zurbrügg, C. (2014) *Compendium of Sanitation Systems and Technologies, 2nd Revised Edition*, Dübendorf: Swiss Federal Institute of Aquatic Science and Technology (Eawag).

Udert, K., Larsen, T. A. and Gujer, W. (2006) Fate of major compounds in source-separated urine. *Water Science and Technology, 54*(11-12), pp. 413-420.

Udert, K. and Wächter, M. (2012) Complete nutrient recovery from source-separated urine by nitrification and distillation. *Water Research, 46*(2), pp. 453-464.

Udert, K. M., Larsen, T. A. and Gujer, W. (2003) Estimating the precipitation potential in urine-collecting systems. *Water Research, 37*(11), pp. 2667-2677.

UN (2000) *UN Millennium Development Goals (MDG)*, Available: http://www.un.org/millenniumgoals/.

UN (2015a) *The Millennium Development Goals Report*, Available: http://www.un.org/millenniumgoals/2015_MDG_Report/pdf/MDG%202015%20rev%20(July%201).pdf.

UN (2015b) *Sustainable Development Knowledge Platform*, Available: https://sustainabledevelopment.un.org/.

USEPA (1979) *Methods for chemical analysis of water and wastes*, Cincinnati: U.S. Environmental Protection Agency.

Vickers, A. L. (1999) *Handbook of water use and conservation,* Amherst, MA: WaterPlow Press.

Villa-Castorena, M., Ulery, A. L., Catalán-Valencia, E. A. and Remmenga, M. D. (2003) Salinity and nitrogen rate effects on the growth and yield of chile pepper plants. *Soil Science Society of America Journal, 67*(6), pp. 1781-1789.

Vinnerås, B. and Jönsson, H. (2002) The performance and potential of faecal separation and urine diversion to recycle plant nutrients in household wastewater. *Bioresource Technology, 84*(3), pp. 275-282.

von Münch, E. and Ingle, R. (2012) Compilation of 25 case studies on sustainable sanitation projects from Africa. *Sustainable Sanitation Alliance (SuSanA) and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Germany*.

Wagner, M. and Loy, A. (2002) Bacterial community composition and function in sewage treatment systems. *Current opinion in biotechnology, 13*(3), pp. 218-227.

Wanapat, M. and Cherdthong, A. (2009) Use of real-time PCR technique in studying rumen cellulolytic bacteria population as affected by level of roughage in swamp buffalo. *Current microbiology, 58*(4), pp. 294-299.

Wanapat, M., Sundstøl, F. and Garmo, T. (1985) A comparison of alkali treatment methods to improve the nutritive value of straw. I. Digestibility and metabolizability. *Animal Feed Science and Technology*, *12*(4), pp. 295-309.

WHO (2015) *Sanitation Safety Planning: Manual for Safe Use and Disposal of Wastewater Greywater and Excreta,* World Health Organization.

WHO/UNICEF (2017) Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines.

Wilsenach, J., Schuurbiers, C. and Van Loosdrecht, M. (2007) Phosphate and potassium recovery from source separated urine through struvite precipitation. *Water Research, 41*(2), pp. 458-466.

Winker, M., Tettenborn, F., Faika, D., Gulyas, H. and Otterpohl, R. (2008) Comparison of analytical and theoretical pharmaceutical concentrations in human urine in Germany. *Water Research, 42*(14), pp. 3633-3640.

Winker, M., Vinnerås, B., Muskolus, A., Arnold, U. and Clemens, J. (2009) Fertiliser products from new sanitation systems: their potential values and risks. *Bioresource Technology, 100*(18), pp. 4090-4096.

Xinhua (2017) *Why Xi is talking about the 'toilet revolution'*, Available: http://www.ecns.cn/2017/11-28/282418.shtml [Accessed December 22 2017].

Xu, G., Fan, X. and Miller, A. J. (2012) Plant nitrogen assimilation and use efficiency. *Annual review of plant biology, 63*, pp. 153-182.

Zaman, M. and Owen, E. (1990) Effect of calcium hydroxide or urea treatment of barley straw on intake and digestibility in sheep. *Small Ruminant Research, 3*(3), pp. 237-248.

Zavala, M. A. L. and Funamizu, N. (2005) Effect of moisture content on the composting process in a biotoilet system. *Compost science & utilization, 13*(3), pp. 208-216.

Zavala, M. L., Funamizu, N. and Takakuwa, T. (2005) Biological activity in the composting reactor of the bio-toilet system. *Bioresource Technology, 96*(7), pp. 805-812.

Zhang, J., Giannis, A., Chang, V. W., Ng, B. J. and Wang, J.-Y. (2013) Adaptation of urine source separation in tropical cities: process optimization and odor mitigation. *Journal of the Air & Waste Management Association, 63*(4), pp. 472-481.

Zhang, J., She, Q., Chang, V. W., Tang, C. Y. and Webster, R. D. (2014) Mining nutrients (N, K, P) from urban source-separated urine by forward osmosis dewatering. *Environmental Science & Technology, 48*(6), pp. 3386-3394.

Zhu, S. and Chen, S. (2002) The impact of temperature on nitrification rate in fixed film biofilters. *Aquacultural Engineering, 26*(4), pp. 221-237.

국문 요약

질산화 미생물을 이용한 자원순환형 화장실에 대한 연구

인류가 탄생한 태초부터 배설 과정은 가장 자연적이고 빈번하게 발생하는 생물학적 과정의 일부이다. 하지만, 현재에도 전 세계적으로 기본적인 위생 시설에 대한 접근성이 부족하기 때문에 이를 개선해야 한다는 시각이 나날이 증가하고 있다. 즉, 현재의 위생 시설로는 지속 가능한 개발 목표 중 여섯 번째 항목(SDG 6)에 해당하는 'Water and Sanitation' 을 해결할 수 없다.

화장실은 인간의 배설 과정이 발생하는 기본적인 위생 시설이다. 이러한 시설에서 발생한 배설물은 물과 혼합되어 같이 처리되어지기 때문에 폐기물을 생산함과 동시에 물의 낭비가 이루어진다. 이를 처리하기 위하여 많은 에너지가 소비되고, 복잡한 공정이 필요하기 때문에 이와 가은 방식은 지속가능하지 못하다.

물과 위생시설 사이에는 악순환이 존재한다. 물의 공급이 없으면 적절한 위생시설이 될 수 없으며, 적절한 위생시설이 갖추어져 있지 않으면 물의 공급이 줄어든다. 이러한 악순환을 끊고, 적절하고 평등한 위생 시설을 구축하기 위한 접근이 필요하다. 특히, SDG 6.2 는 개방형 배변을 종식시키는 것을 목표로 하여 여성의 이용 및 취약한 상황의 해결에 초점을 두는데, 이는 비누와 물로 손을 씻는

기본적인 시설을 포함하여 안전하게 관리되는 위생 서비스를 사용하는 인구의 비율이 지표가 될 수 있다. 단, 이러한 지표는 사용 가능한 담수의 양과 처리해야하는 폐수의 양을 고려하지 않고 산정이 된다.

결과적으로, 위생 시설의 새로운 패러다임에서는 위생 시설 자체의 문제를 해결하는 것에 국한되지않고, SDG 6.2 를 위한 새로운 지표로 고려될 수 있는 방향으로 나아가야한다. 본 연구에서는 자원 순환 위생시설(RCS)을 SDG 6.2 의 해결책으로 제시하였다. RCS 시스템은 소변과 대변을 분리하고, 현장에서 처리하여 비료로 활용함으로써 물과 에너지 소비를 줄일 수 있으며, 유지 관리 측면에서도 쉽고 비용이 저렴하다는 장점이 있다.

RCS 시스템은 세가지 부분으로 구성되어 있다. 변기 부분은 소변과 대변을 분리하는 역할을 하며, 소변과 대변의 각 처리 장치는 적합한 기준을 충족시킬 수 있도록 설계되었다. 이러한 시설은 제한적인 현장 처리와 낮은 청결도, 발생하는 냄새와 문화적인 차이에서 발생하는 문제점을 해결해야 한다.

이러한 문제점들을 과학적으로 해결하기 위하여, 대변에서 소변을 분리하여 적용하는 생물학적 처리 방법을 제안하였다. 이 방법은 표준 비료의 기준을 충족시킬 뿐만 아니라 발생하는 냄새와 큰 부피와 같은 다른 부수적인 문제를 극복할 수 있었다.

또한 RCS 시스템에서 발생하는 냄새를 해결하기 위하여 빗물 활용 시설을 제안하였다. 이러한 빗물의 이용은 효율적으로 문제를 극복할 수 있기 때문에 유지 보수를 위해 소비되는 물의 양을 최적화 할 수 있었다.

RCS 시스템의 현장 적합성과 효율성을 검증하기 위해 도시 농업 센터에 설치하여 연구를 진행하였다. 작물의 재배에 있어서 가장 효과적인 비료를 분석하기 위하여 시중에서 판매되는 기존 비료와 RCS 시스템으로 처리된 분뇨에서 생산한 비료를 각각 사용하여 무를 재배하였다. 실험 결과, RCS 시스템으로 생산한 비료가 시중에 판매되는 비료보다 우수한 결과를 도출하였다.

결론적으로, SDG 6 를 효과적으로 해결하기 위해서는 더 이상 인간의 배설물을 폐기물로 간주하지 않고, 자원으로 바라보는 시각의 변화가 이루어져야 한다.

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