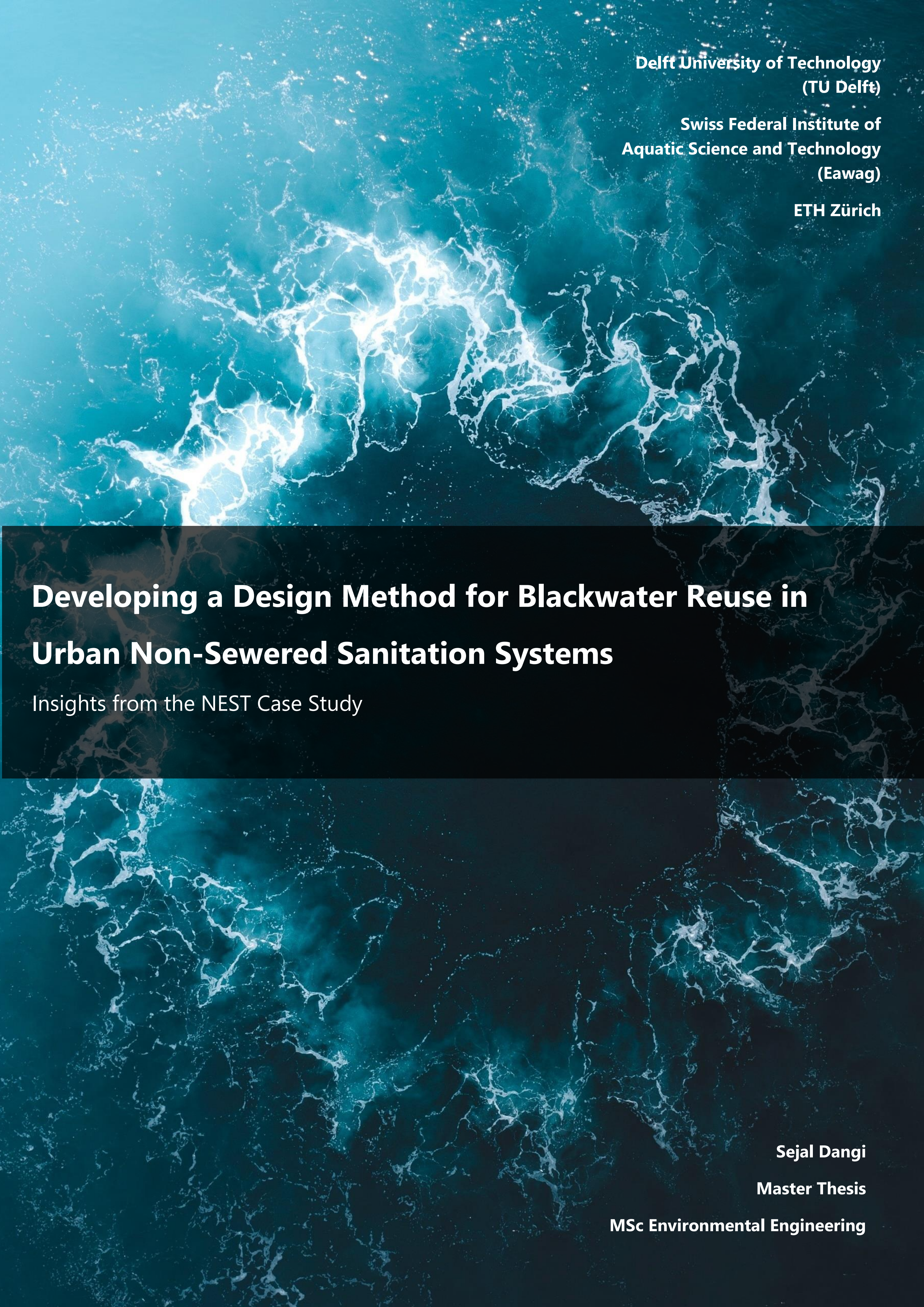

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(TU Delft)

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Aquatic Science and Technology
(Eawag)

ETH Zürich

Developing a Design Method for Blackwater Reuse in Urban Non-Sewered Sanitation Systems

Insights from the NEST Case Study

Sejal Dangi

Master Thesis

MSc Environmental Engineering

Developing a Design Method for Blackwater Reuse in Urban Non-Sewered Sanitation Systems

Insights from the NEST Case Study

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

Master of Science

in Environmental Engineering

Faculty of Civil Engineering and Geosciences

By

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To be defended in public on 9th July, 2024

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Cover art from Freepik.com

Acknowledgements

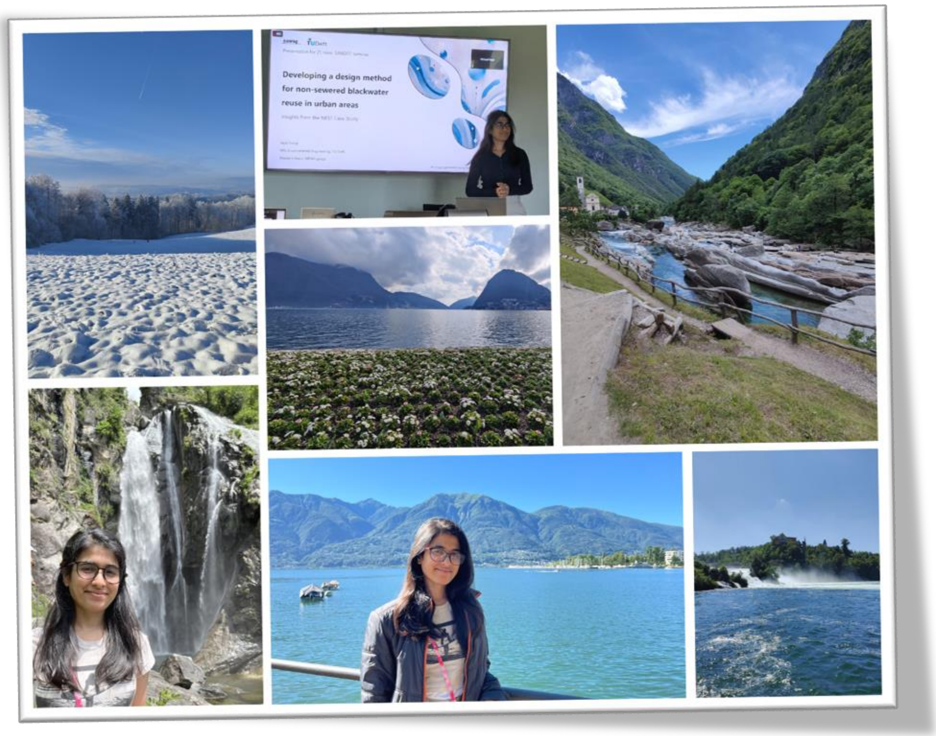
This document represents the final version of my thesis submitted for the Master's programme in Environmental Engineering at TU Delft. I worked on this thesis from January 2024 to June 2024, both at TU Delft and at the Swiss Federal Institute of Aquatic Science and Technology (Eawag).

I would like to express my gratitude to Dr. Linda Strande and the MEWS group at Eawag for the opportunity to work on this thesis. Since discovering Eawag in 2018, I have aspired to work here (and in Switzerland), and this experience has been the fulfilment of a long-held ambition. I am particularly thankful to Michael Vogel, my daily supervisor, for the weekly meetings and detailed discussions that provided clarity and more importantly motivation to keep going. Linda's insightful comments throughout have significantly improved my thinking and writing, for which I am deeply grateful.

My sincere thanks go to Merle de Kreuk and Helena Verloo for facilitating the connection with Eawag and to Merle for the technical discussions that always left me fascinated with biological wastewater treatment. Additionally, I appreciate the support from Merle and Maurits in applying for the Van Effen Research Grant, without which this trip to Switzerland would not have been possible. Thank you, Mariska, for helping me present my work cohesively and engagingly.

I would also like to thank Prof. Eberhard Morgenroth for his support with the research grant application and TU Delft for the Van Effen Master's Scholarship along with the numerous opportunities to curate my educational journey. The last two years have been a period of significant professional and personal growth, made possible only by TU Delft's incredible and flexible learning environment.

Finally, I would like to express my heartfelt gratitude to Mummy, Papa and my brother, Nirav, for their unwavering support; to Archisha, Manav, Abhishek, and Anuj for always being my greatest champions; and to Saurabh, my mentor, for the inspiration, encouragement, and collaborative brainstorming, that has been instrumental in my journey in the WASH sector.



Summary

Non-sewered sanitation systems have been recognized as a valuable complement to sewered sanitation for over two decades (Strande, 2024). However, our scientific and operational understanding of these systems is still evolving. In urban areas of low- and middle-income countries, non-sewered sanitation could prevent nearly 600,000 deaths caused due to inadequate sanitation infrastructure and the discharge of untreated wastewater. As these regions experience rapid urban expansion, sewered systems struggle to keep pace, exacerbating the situation. In high-income countries, where sewered systems are reaching capacity and resource recovery is increasingly important, non-sewered sanitation offers a valuable alternative. Urbanization increases demand for water, while climate change is causing our natural water resources to shrink, highlighting the need to rebalance the urban water cycle (Konapala et al., 2020; Reymond et al., 2016). By treating and reusing wastewater close to the source, non-sewered approaches can prevent environmental degradation, mitigate water stress, and help close the urban water cycle. Thus, now is the perfect time to focus research and implementation efforts on safe and reliable wastewater reclamation using urban non-sewered sanitation systems.

Blackwater (wastewater from toilets) treatment and reclamation in non-sewered sanitation systems is particularly challenging due to its high organic content, high variability, and low public acceptance. However, approximately 20,000 liters of freshwater per person are consumed annually for toilet flushing—enough to fulfill an individual's drinking water needs for 15 years (Beler-Baykal, 2015; Sawka et al., 2005). As long as flush toilets remain the standard, this demand will persist. Therefore, blackwater reclamation offers a promising solution to reduce freshwater extraction and prevent the discharge of untreated wastewater into the environment.

Research on water recovery from blackwater has only gained attention in the last 20 years, and there is a lack of knowledge on designing treatment trains for blackwater reclamation in urban areas, especially for mechanically dewatered blackwater—a low-footprint and robust alternative to established dewatering technologies. Current research often focuses on developing individual technologies rather than producing comprehensive approaches that allow for the selection of technologies along the treatment chain based on specific contexts, such as an apartment building or an urban community (Strande, 2024).

Additionally, greenhouse gas emissions from non-sewered sanitation systems have recently been highlighted due to their significant contributions. Yet, the carbon footprint of a complete non-sewered system, including treatment and reuse of all wastewater streams and urine concentration for fertilizer production, has not been quantified.

Therefore, to provide solutions for developing climate-resilient, safe, and sustainable non-sewered systems for blackwater reuse, this thesis focuses on three main parts:

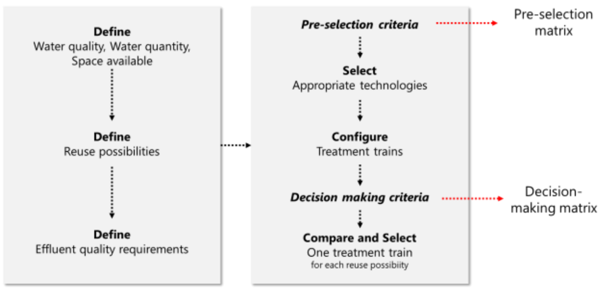
- Developing a methodology to select technologies along the treatment train for blackwater reuse
- Quantifying the carbon footprint of a complete non-sewered sanitation system including treatment and reuse of greywater, urine, and brownwater
- Assessing the relevance of blackwater reuse in urban communities worldwide

The NEST building in Switzerland was selected as a case study to demonstrate the application of the approaches and solutions developed in this thesis.

Select technologies and configure treatment trains

To select appropriate technologies for reclaiming mechanically dewatered blackwater, the first step consists of defining the characteristics of the urban community, such as space available, water quality,

quantity, reuse possibilities, and applicable effluent compliance standards. With these characteristics defined, a literature review was conducted to compile a long-list of technologies suitable for blackwater reuse. This list was then refined using a set of pre-selection criteria. A pre-selection matrix was developed that groups technologies according to the pre-selection criteria and assists other researchers in choosing technologies that fit their specific urban contexts. The selected technologies were configured into treatment trains. The treatment trains were then compared using 14 decision-making criteria that evaluate their social, technical, economic, and environmental sustainability and one treatment train was selected. The decision-making criteria have global relevance and ensure comprehensive evaluation. The proposed methodology is visually represented in the schematic provided below.



Applying the above methodology for a hypothetical urban community of 2000 residents surrounding the NEST building in Switzerland, the most suitable treatment train for non-potable reuse applications (e.g., toilet flushing) was determined to be a moving bed biofilm reactor, chemical precipitation, ultrafiltration, granular activated carbon, and UV disinfection considering the ISO 30500:2018 standard for effluent quality. The most-suitable treatment train for indirect potable reuse applications (e.g., recharge of drinking water reservoir) was moving bed biofilm reactor, chemical precipitation, ultrafiltration, nanofiltration, granular activated carbon, and UV disinfection.

An advantage of this methodology is its adaptability: the pre-selection matrix can be adjusted based on local expertise to include emerging technologies, while the decision-making criteria can be weighted differently to select unique treatment trains for specific urban communities. This approach provides flexibility for contextualization and optimization.

Calculate carbon footprint of a complete non-sewered sanitation system

After selecting a treatment train in the previous step, static design modelling was conducted using BioWin to determine unit sizes of the selected technologies. These unit sizes were utilised for subsequent carbon footprint calculations.

The theoretical evaluation of the carbon footprint focused on a non-sewered sanitation system incorporating brownwater (90% urine separation), greywater, and urine treatment and concentration for fertiliser production. The carbon footprint was calculated using the IPCC emission factor approach. The process design considered for urine treatment and concentration, and greywater treatment, were adapted from existing units in the NEST building, while the process design considered in carbon footprint calculations for brownwater treatment was designed in this thesis.

The primary contributor to the total carbon footprint were indirect emissions from electricity consumption, when a predominantly fossil fuel mix was considered for power generation. The urine concentration unit, consuming 107 kWh/m^3, surpassed the electricity consumption from all other units combined (20 kWh/m^3), substantially elevating the carbon footprint of the non-sewered system compared to previously reported sewered systems (0.5-3 kgCO_2-e/m^3). However, caution is advised in direct comparisons, as most studies in literature that calculate the carbon footprint of sewered sanitation systems do not account for the emissions due to sewer construction. Transitioning to renewable energy could potentially slash the carbon footprint of the non-sewered systems by up to 80%, offering a promising mitigation strategy.

In this thesis, the analysis did not include benefits like carbon emissions reduction from reduced freshwater extraction. These avoided burdens should be quantified to present a realistic picture of the environmental sustainability of non-sewered sanitation, underscoring the need for comprehensive life cycle cost and benefit evaluations by future researchers.

Nonetheless, the preliminary carbon footprint analysis sheds light on key contributing factors, and serves as a foundational basis for future researchers to optimize solutions for wastewater resource recovery.

Assess the feasibility of applying methods and results in urban communities

The treatment trains and static designs produced in the previous step were critically evaluated for their feasibility for on-ground implementation in the NEST and other urban communities in low, middle and high income countries. An uncertainty analysis was performed to evaluate the impact of variability in design input (e.g., degree of urine separation) on the unit sizes of the treatment technologies. This uncertainty analysis serves as a basis to evaluate how the design could be simplified for on-ground implementation. Using the results from uncertainty analysis and the static design, a process design for implementation in the NEST was communicated using a piping and instrumentation diagram.

In low-income countries, where less than 15% of the urban population has access to sewers, knowledge about selecting appropriate technologies for non-sewered sanitation presented in this thesis is highly relevant. Simple and robust technologies are essential here, given frequent power cuts and high maintenance costs associated with more advanced systems. The methodology developed in this thesis offers flexibility to select treatment technologies and configure treatment trains for these settings, by weighing the decision-making criteria related to energy use and maintenance highly as compared to others.

Middle-income countries face challenges with wastewater treatment infrastructure that include operational issues and varying levels of financial support. While these countries have higher coverage of sewers compared to low-income counterparts, there are still gaps in system reliability and maintenance. Therefore, non-sewered sanitation is also relevant in this context. The choice of technology is crucial, with a need to explore alternatives that balance efficiency with operational ease. For instance, ultrafiltration is operationally expensive to maintain and users may be reluctant to adopt this technology in real-life. The methodology developed in the thesis provides a framework for selecting and designing treatment trains that align with these considerations, promoting sustainable wastewater management.

In high-income countries, where sewer coverage is extensive but aging, non-sewered systems offer sustainable alternatives. These systems can mitigate the ecological impacts of centralized sewer systems while providing resilience against climate change and water scarcity. Public acceptance and regulatory frameworks play significant roles in the adoption of non-sewered systems, particularly concerning the reuse of recovered water and nutrients. Therefore, in high-income countries, to reap the full benefits of non-sewered systems, legislation must co-evolve with technology.

In summary, growth in scientific research on non-sewered sanitation must go hand in hand with the development of operational knowledge to bring it to the same maturity level as sewered sanitation (Strande, 2024). This thesis establishes a framework for designing safe, reliable, and environmentally sustainable non-sewered sanitation systems for blackwater treatment and reuse in urban areas, addressing a notable gap in current literature. It urges future researchers to undertake pilot testing to validate these theoretical frameworks.

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Introduction

1 Introduction

1.1 Background

Non-sewered sanitation systems have been recognized as a valuable complement to sewered sanitation for more than two decades (Strande, 2024). Currently, these systems serve 64% of the global urban population (UNICEF & WHO, 2023), and the population not connected to sewers is growing twice as fast as the ones connected to them (Reymond et al., 2016). Despite this, our scientific and operational understanding of non-sewered infrastructure is still evolving (Strande, 2024). As sewered sanitation struggles to keep pace with rapid urban expansion in the twenty-first century (Öberg et al., 2020), now is the ideal time to expand research and implementation efforts on non-sewered sanitation (Strande, 2024).

Inadequate sanitation infrastructure results in the discharge of untreated wastewater into the environment, causing environmental degradation and ~600,000 deaths annually (WHO, 2023). At the same time, an increasing demand for water driven by urbanization, combined with shrinking natural water resources due to climate change, underscores the need to rebalance the urban water cycle (Konapala et al., 2020; Reymond et al., 2016). Non-sewered approaches can support the separate collection and treatment of wastewater streams (for e.g., household wastewater is collected and treated separately from industrial wastewater). This simplifies wastewater treatment, thereby facilitating water recovery and localized reuse. Non-sewered sanitation systems, by effectively treating and reusing wastewater close to the source, can prevent environmental degradation, mitigate water stress, and help close the urban water cycle. Recognizing the critical link between clean water, sanitation, and wastewater management, these systems can enhance community health and environmental sustainability in urban areas by efficiently capturing, conveying, and treating wastewater for reuse (Strande et al., 2023; Tortajada, 2020).

Non-sewered sanitation systems handle wastewater without relying on sewers. The wastewater can be transported by road for further treatment (e.g., using trucks), conveyed via pipes for near-source treatment (e.g., within a building), or treated completely at the source (e.g., urine and feces are collected and treated within a toilet) (Strande et al., 2023). The definition adopted in this thesis is that of a sanitation system that is connected to a water supply and where wastewater is collected by means of pipes from a number of apartments within an urban community and treated within this community for safe discharge or reuse.

1.2 Problem description

The wastewater collected from households (domestic wastewater) consists of two fractions: Blackwater (urine, faeces, flush water, and anything else that goes into a toilet, e.g., toilet paper), and greywater (wastewater from showers, sink, laundry, and dishwashers) (Beler-Baykal, 2015). When urine is collected separately, the remaining blackwater is termed as brownwater (Beler-Baykal, 2015). Separate collection and treatment of urine, brownwater and greywater is known as source-separation. Urine contains most of the nutrients (85–90 % of nitrogen, 50–80% of phosphorus) (Sohn et al., 2023) while greywater contains almost no pathogens (Shaikh & Ahammed, 2020). Source-separation not only simplifies treatment of each liquid stream but also enhances the potential for safe recovery of water and other products, such as energy and nutrients from the wastewater (de Simone Souza et al., 2023).

While greywater and urine reclamation have been extensively researched, blackwater reclamation has only recently gained attention (Bracken et al., 2007; Pinto et al., 2021; J. Xu et al., 2023a). This is primarily due to the unique challenges it presents, such as its high organic content (260-8700 mgCOD/L, when compared to 130-389 mgCOD/L for domestic wastewater), high variability in load quantities and characteristics, and low public acceptance (Hurlimann et al., 2007; J. Xu et al., 2023a). However, approximately 20,000 liters of freshwater are consumed per person annually for toilet flushing, which is enough to fulfill an individual's drinking water needs for 15 years (Beler-Baykal, 2015; Sawka et al., 2005). As long as flush toilets remain the gold standard for human waste collection and transport, this demand for water is unlikely to diminish. Therefore, blackwater reclamation offers a promising solution to reduce freshwater extraction.

Recognizing both the challenges and benefits of blackwater reclamation, the Management of Excreta, Wastewater, and Sludge group (MEWS) at the Swiss Federal Institute of Aquatic Science and Technology (Eawag) aims to develop reliable and safe technologies for blackwater treatment and reclamation in urban non-sewered sanitation systems.

The first step in blackwater reclamation is dewatering, i.e., separation of solids and liquids as blackwater contains less than 5% solids (Velkushanova et al., 2021a). In urban areas with limited space and operator availability, dewatering technologies must be low-footprint and adaptable to changes in system input. Previous research by the MEWS group has demonstrated the effectiveness of flocculation for solid-liquid separation in handling highly variable influent blackwater compositions (Shaw et al., 2022). Additionally, flocculation and settling can be followed by mechanical dewatering to further compact the solids. Mechanical dewatering offers advantages over other established dewatering technologies, such as settling/thickening tanks, imhoff tanks, or drying beds, due to its significantly lower footprint (Strande et al., 2014). Building upon this knowledge, the MEWS group is currently piloting an innovative dewatering process in the NEST building in Switzerland, as depicted in **Figure 1**. This system combines flocculation with a screw press, aiming to achieve low-footprint, predictable, and automated dewatering. The choice of selecting the NEST building for testing is strategic, providing a unique environment that encompasses living, recreational, and working spaces, thus ensuring that data collected here reflects realistic conditions as opposed to laboratory settings (EMPA, 2024).

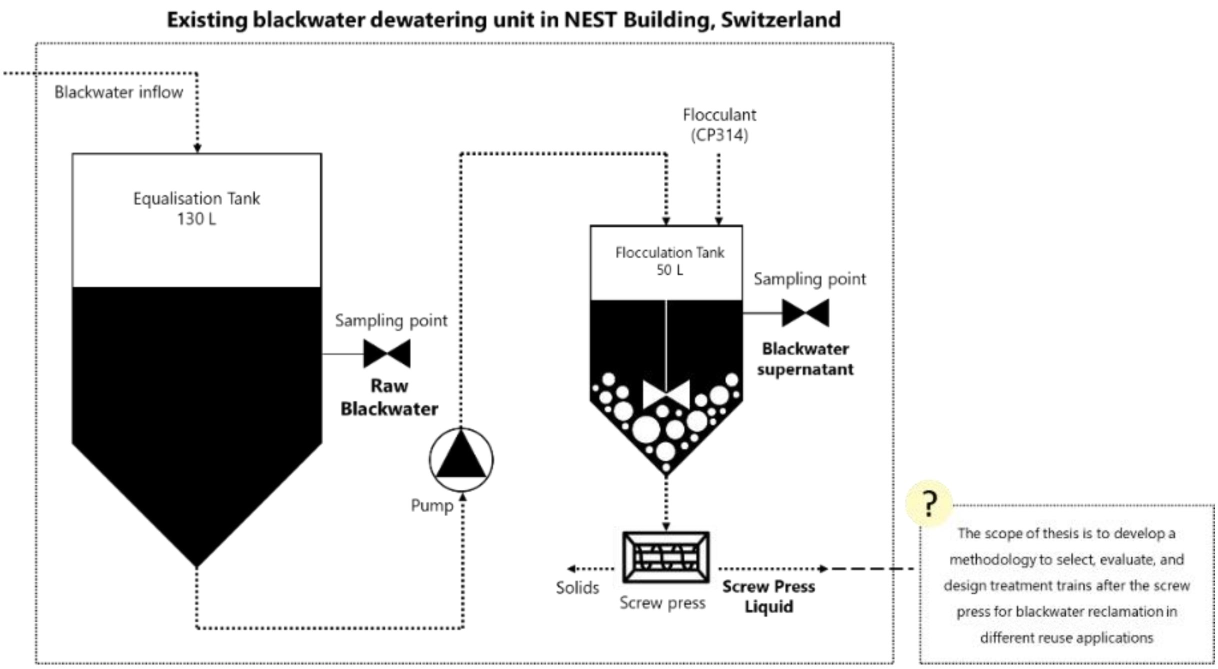


Figure 1: Schematic representation of blackwater dewatering unit currently being pilot tested in the NEST building in Switzerland by the Management of Excreta, Wastewater, and Sludge group (MEWS) at the Swiss Federal Institute of Aquatic Science and Technology (Eawag). It consists of an equalisation tank, a pump, a flocculation tank, and a screw press. The scope of the thesis is also indicated with respect to the existing system.

The liquid discharged from the screw press needs further treatment before it can be reused, as it contains high levels of nutrients and pathogens (Anusuyadevi et al., 2023). However, there is a lack of information regarding the selection, evaluation, and design of appropriate treatment trains for reclaiming this liquid to reuse it in applications with varying degrees of public use restrictions (e.g., swimming or toilet flushing). In general, current research on non-sewered sanitation focuses on development of individual technologies rather than development of a comprehensive approach that allows for selection of technologies along the treatment chain based on specific contexts (Strande, 2024), such as, an apartment building in a high-income country or an urban community in a middle-income country.

Therefore, the primary objective of this thesis is to develop a methodology that the MEWS group and other researchers, engineers, planner or managers can use to select technologies, evaluate their trade-offs and design non-sewered treatment trains for blackwater reclamation in urban communities. The urban community under consideration here is a formal settlement, indicating that the community has access to public services, including piped connections to water. The methodology was developed considering a hypothetical, but real-world scenario of an urban community comprising 2000 residents, housed in 6-8 buildings surrounding the NEST building in Switzerland. This community can be visualized as depicted in **Figure 2**. The last part of the thesis will explore how the methodology and findings can be applied to other urban communities in low, middle or high-income countries.

In addition, there is increasing recognition of the role that sanitation systems play in contributing to global greenhouse gas (GHG) emissions, and consequently, to climate change (Lambiasi et al., 2024). Understanding the characteristics of and measuring GHGs generated during wastewater treatment is essential for developing strategies to mitigate these human-induced emissions. Although emissions from sewered treatment plants have been previously quantified (Lambiasi et al., 2024), GHG emissions from a complete non-sewered sanitation system—including the collection, treatment, and reuse of all domestic wastewater streams (brownwater, urine, and blackwater)—have not been quantified before to the best of author's knowledge.

Therefore, a secondary, yet an important, objective is theoretically estimate the GHG emissions from the non-sewered sanitation system. The aim is to motivate future researchers to conduct monitoring campaigns, thereby building upon the results.

Figure 2: Artistic representation of an urban community of 2000 people as a formal settlement connected to public services such as piped water connection. Image retrieved from Skyline Architectural Consultant (Skyline Architectural Consultant, 2024).

1.3 Research questions

The thesis aims to develop a methodology to select technologies, evaluate their trade-offs and design blackwater reclamation systems in formal urban settlements. The main research question that will be answered is:

What treatment trains are most suitable for reclaiming blackwater following dewatering with flocculants and a screw press?

Sub-questions to be answered are:

- What data is required to design a treatment train for blackwater reclamation?
- How can decision-making processes be used to select treatment trains for different reuse possibilities?
- How can a static design model be used to select a suitable reuse possibility for pilot testing by future researchers?
- What is the carbon footprint of a complete non-sewered sanitation system?
- Can the treatment train for the reuse possibility be implemented in the NEST and other urban communities?

1.4 Overview of the methodology

The research questions and the sub-questions presented above represent different steps of the methodology developed as a part of this thesis. These steps are outlined below and a schematic representation is provided in **Figure 2**.

Step 1 consists of defining the characteristics of the urban community such as quality and quantity of blackwater collected, the reuse possibilities, the space available, and the effluent quality targets that must be complied with.

Step 2 consists of selecting technologies for different reuse possibilities and boundary conditions defined in the previous step. First, pre-selection criteria are established to assist readers in narrowing down from a long-the list of technologies. This serves as an initial filtering step since not all technologies are suitable for application in all urban communities. Once the technologies are selected, they are configured into treatment trains. These treatment trains are designed such that theoretically they should be capable of meeting the effluent quality targets specified in the previous step. It was hypothesized that multiple treatment trains may be capable of meeting the specified standards. Therefore, the next step was to define and adopt decision-making criteria to select one treatment train from all treatment trains designed. This is a detailed evaluation and the decision-making criteria are globally applicable.

Step 3 consists of performing unit sizing calculations for the one selected treatment train and developing a static design model. This static model acts as a foundation for more detailed modeling by future researchers and offers insight into the feasibility of pilot testing the concept. Additionally, an uncertainty analysis was also conducted to assess the impact of design assumptions on unit sizing. Finally, the carbon footprint of a non-sewered sanitation system was calculated to document its environmental sustainability.

Step 4 consists of evaluating how the most suitable reuse possibility can be pilot tested in the NEST. A process design for implementing the treatment train in the NEST is proposed. This design is tailored to the unique characteristics of the NEST, and it may not be directly applicable to other urban communities. Therefore, discussions are provided on how to adapt the methodology depicted in **Figure 3** and the results obtained in Steps 1 to 4 to apply it in other urban communities in high-, middle-, or low-income countries.

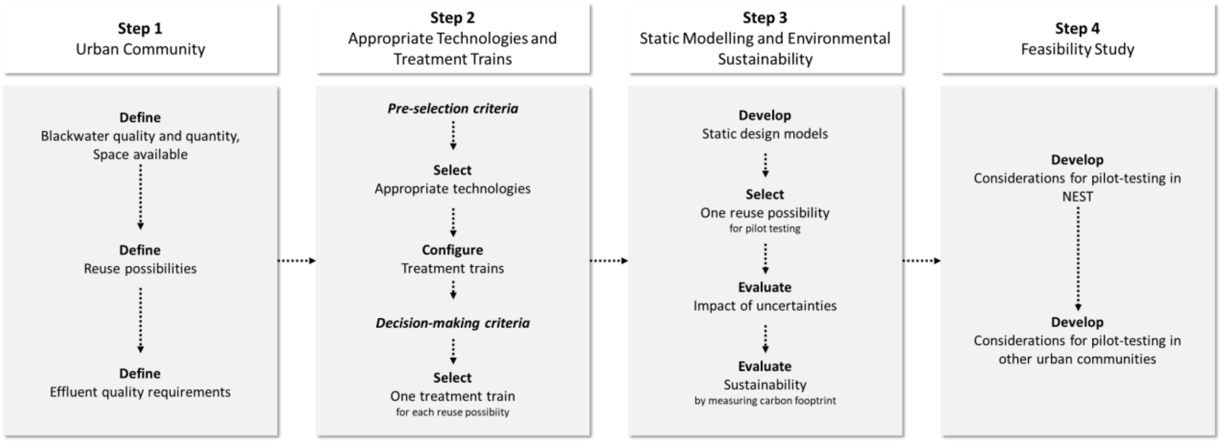


Figure 3: Flow chart representing the methodology developed during this thesis to assist researchers, engineers, planner or managers in selecting technologies, evaluating their trade-offs, and designing treatment trains for non-sewered blackwater reclamation systems in urban areas.

Theoretical Background

2 Theoretical Background

2.1 Terminology

The definitions of various terms necessary to understand the topic and research question are presented below.

Non-sewered sanitation systems. Non-sewered sanitation encompasses systems where wastewater is not transported via sewers (Strande et al., 2023). The wastewater can be transported by road for further treatment (e.g., by using trucks), by pipes and treated close to the source (e.g., collected and treated within a building), or treated completely at source (e.g., urine and feces are treated within the toilet where they are also collected) (Strande et al., 2023). The terms 'on-site', 'off-grid', 'fecal-sludge management', 'off-site', 'decentralised', and 'semi-centralised' are often used to describe different types of non-sewered sanitation system (Strande et al., 2023). The definition used in this thesis is that of a sanitation system that is connected to a water supply and where wastewater is collected by means of pipes from a number of apartments within an urban community and treated within this community for safe discharge or reuse.

Domestic wastewater. This water exclusively comprises human body waste, human liquid waste, and water resulting from washing activities, such as, shower/bath, sink, laundry, or dishwasher. It does not incorporate any discharges from commercial or industrial sources (International Organization for Standardization, 2019).

Municipal wastewater. Municipal wastewater, or wastewater in a sewer system, is different from domestic wastewater, as it also includes clean water used for transportation in sewer networks, rainwater, or contributions from agriculture or industry (International Organization for Standardization, 2019).

Blackwater. Originates from toilets and includes urine, faeces, flush water, and anything else that goes into a toilet, for e.g., toilet paper (Beler-Baykal, 2015).

Greywater. Encompasses wastewater from all sources except the toilet such as showers, sink, laundry, and dishwashers (Beler-Baykal, 2015).

Blackwater supernatant. In this thesis, blackwater supernatant is defined as the liquid left in the flocculation tank after solid-liquid separation through settling (**Figure 1**).

Screw press liquid. In this thesis, the term screw press liquid defines the liquid left after mechanical dewatering in the press (**Figure 1**).

Blackwater effluent. In this thesis, blackwater effluent is the liquid leaving the non-sewered sanitation system designed for blackwater reclamation.

Source separation. Source separation is the practice of separating various wastewater streams such as greywater and blackwater or it can also mean the separate collection of urine, brownwater, and greywater (McConville et al., 2017).

Blackwater reclamation. The act of treating blackwater to make it suitable for reuse (US EPA, 2012). It is used interchangeably with blackwater reuse or blackwater recycling.

Primary treatment. This is the first step in wastewater treatment. It deals with removal of large suspended solids and is often accomplished by means of screens, grit chambers and sedimentation tanks (US EPA, 1998). In this thesis, the equalisation tank, the flocculation tank and the screw press provide primary treatment for blackwater (**Figure 1**).

Secondary treatment. This is the second step in wastewater treatment. This step consists of biological degradation of suspended or dissolved organic matter. Aerobic or anaerobic conditions may be used for microbial growth and the microorganisms may be grown on fixed support media or secondary treatment technologies may support the growth of bacteria directly into the sludge (US EPA, 1998).

Tertiary treatment. This is the third step in wastewater treatment. Typically, this step is used to remove dissolved substances and pathogens (LibreTexts, 2024). This can be achieved using technologies such as granular activated carbon, chlorine, UV, or membrane processes (US EPA, 2012).

Advanced treatment. This is an extra step in wastewater treatment which is used to remove trace contaminants and is especially required when the wastewater is to be reused. This can include processes such as chemical clarification, carbon adsorption, nanofiltration, reverse osmosis, advanced oxidation, air stripping, ultrafiltration, or ion exchange (US EPA, 2012).

Treatment train. In this thesis, when secondary, tertiary, and/or advanced treatment technologies are combined together for complete wastewater treatment and reclamation, the combination is called as a treatment train.

Intergovernmental Panel on Climate Change (IPCC) and Emission Factors. IPCC is a United Nations intergovernmental organization tasked with advancing scientific understanding of climate change resulting from human activities (IPCC, 2024). The IPCC has developed emission factors for different human activities. Emission factors are coefficients that quantify the emission or removal of a greenhouse gas per unit activity (IPCC, 2019). Other independent authorities have also developed databases of emission factors. For instance, Institute for Global Environmental Strategies has developed a list of emission factors for production of electricity in different countries (Tsukui et al., 2024a)). The three most important greenhouse gases emitted during domestic wastewater treatment are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Bartram et al., 2019).

Pre-selection criteria. In this thesis, pre-selection criteria are defined as any criteria that can be used to pre-screen technologies from a long-list. These criteria only allow for preliminary selection rather than a detailed comparison.

Decision-making criteria. In this thesis, decision-making criteria are defined as those criteria that allow comparison of treatment trains. The decision-making criteria are used for a detailed evaluation of treatment trains whereas the pre-selection criteria are used for pre-screening technologies, removing the ones that are not relevant to the local contexts.

2.2 Community scale blackwater reclamation

Historically, most research has centred on urine treatment and recovery of solids from blackwater for reuse in agriculture. However, the volume of blackwater discharged from flushing toilets underscores the critical need for effective blackwater reuse (J. Xu et al., 2023a). Knowledge from municipal wastewater treatment cannot be directly applied to non-sewered systems because blackwater exhibits variability in total solids, organic matter, and nutrients that is 1–2 orders of magnitude greater (Shaw et al., 2022). However, several researchers have successfully adapted wastewater treatment technologies for use with blackwater. These technologies and treatment trains are detailed in **Table 1**, which includes applications specifically for blackwater reuse. The information in **Table 1** is based on a literature review of 48 peer-reviewed articles as listed in **Appendix 1**.

Based on **Table 1**, blackwater reuse has been implemented in various countries and applications. Technologies applied for secondary treatment include constructed wetlands, waste stabilization ponds, membrane bioreactors, moving bed biofilm reactors, activated sludge, and anaerobic treatment. Common technologies employed for tertiary treatment include UV disinfection, electrochemical disinfection, and chlorination, while advanced treatment often involves membrane filtration and granular activated carbon. In high-income countries such as the Netherlands, Germany, Sweden, and Belgium, biogas production is a predominant reuse application, where blackwater is co-treated with kitchen waste. In Belgium, the effluent from blackwater treatment is also co-treated with greywater to produce process water for industry. This approach could also be a relevant solution for the urban community considered in this thesis. The literature review highlights a research gap in the mechanical dewatering of blackwater, a low-footprint, robust alternative for urban areas developed by the MEWS group. Notably, none of the previous studies have utilized this technology.

2.3 Secondary treatment processes

Three secondary treatment processes stand out from the literature review for individual building and urban community-scale blackwater reclamation with underground treatment plants (i.e., the case study considered in this thesis): activated sludge, moving bed biofilm reactor, and membrane bioreactor. A brief desk-review of each technology was conducted as described below to explore their suitability for the urban community considered in this thesis.

Activated sludge. Discovered in 1914, this process has been applied all across the world (Orhon, 2015). Different configurations of the conventional process have evolved over the years, such as extended aeration, oxidation ditch, sequencing batch reactor, to counter the drawbacks of conventional systems and adapt them to small-scale treatment plants (Brault et al., 2022a). Therefore, this process is well established with a large body of operational expertise. One of the drawbacks is the inability to handle shock loading, commonly encountered in small and medium-scale treatment plants where flow rates can fluctuate widely (Sangamnere et al., 2023).

Moving bed biofilm reactor. Developed in the 1980s, employs the benefits of suspended and attached growth processes for robust, compact and simple wastewater treatment (di Biase et al., 2019). As opposed to other attached growth processes (e.g., trickling filters) where the biofilm carriers are fixed to a bed, the biofilm carriers in a moving bed biofilm reactor are suspended using aeration devices. The system has proven to be adaptable to shock loads hypothesized to be due to the high concentration of biomass and large surface area available for microbial growth (Ali et al., 2014; Frankel, 2022). The moving bed biofilm reactor has been installed in more than 50 countries worldwide (di Biase et al., 2019). Drawbacks include requirement of highly skilled operators and nuisance caused due to odors and flies (di Biase et al., 2019).

Membrane bioreactor. Invented in 1969, a membrane bioreactor combines membrane filtration with activated sludge to produce high quality effluent with lower quantities of sludge albeit at higher energy, capital and operational costs (Al-Asheh et al., 2021). The micro- or ultrafiltration membranes used in a membrane bioreactor are different from the conventional membranes, these are specifically designed to handle the excessive solids loading expected in an activated sludge plant. Therefore, procurement issues are common. However, the technology has been successfully applied in middle- and high-income countries with their market share only expected to grow in the future (Judd & Judd, 2011).

Table 1: Results from the literature review on blackwater reclamation systems worldwide are summarized. A comprehensive review, including blackwater treatment units (where reclamation is not practiced), is presented in Appendix 1. The table below provides an indicative, though not exhaustive, summary.

Treatment Train	Reuse application	Location	Scale	Reference
Waste stabilisation ponds and aquaculture	Agriculture Irrigation	India	University campus	(Kumar et al., 2014)
Septic tank, Anaerobic up-flow filter, Horizontal subsurface flow wetland	Landscape Irrigation	Mexico	Food research & development Centre	(de Anda et al., 2018)
Membrane bioreactor	Agriculture Irrigation	Australia	Permanent township frequented by tourists	(Phan et al., 2015)
Screens, Membrane bioreactor, Ozonation	Flushwater	Hamburg	Urban community	(Otterpohl & Buzie, 2011)
Separator, Membrane bioreactor, Electrochemical disinfection	Flushwater, Handwashing, Agriculture Irrigation	Switzerland, South Africa	One public toilet, informal settlement of 500 households, One 14-person household	(Reynaert et al., 2020a)
Solid-liquid separation, Sequencing batch reactor or EcoSan Biodigestor, Coarse Filtration, Electrochemical Reactor, Fine filtration	Flushwater	India, China	12 toilets from different apartments in an urban community	(Varigala et al., 2020)
Vertical flow constructed wetlands	Agriculture Irrigation	Vietnam	Dormitory in an urban community	(X. C. Nguyen et al., 2020)
Coagulation and flocculation, Pneumatic dewatering, Ultrafiltration, Reverse osmosis	Irrigation and Groundwater Recharge	Jordan	University campus	(Kocbek et al., 2022)
Solid-liquid separation, Granular activated carbon, Electrochemical disinfection	Agriculture Irrigation	South Africa	Informal settlement in Durban with 350-400 households	(Sahondo et al., 2020)
Septic tank, Horizontal constructed wetland	Agriculture Irrigation	Saudi Arabia	Village of 2000 people	(El-Rawy et al., 2023)

Screening, Grit chamber, Settling, Activated sludge, Sand filter, Activated carbon, Ultrafiltration, Chlorination	Agriculture Irrigation, Flushwater, Laundry	India	Urban community	(Miorner et al., 2023)
Bar screen, Grit chamber, Moving bed biofilm reactor 1, Moving bed biofilm reactor 2, Sand filter, Activated carbon, Ultrafiltration, Chlorination	Landscape Irrigation, Agriculture Irrigation	India	Urban community	(Schelbert, Luthi, Binz, & Mitra, 2023; Vijayan et al., 2023)
Collection tanks, Biological Treatment, Membrane Filtration, Sodium hypochlorite	Landscape Irrigation, Flushwater	USA	Urban community	(San Francisco Public Utilities Commission, 2021)
Grease traps, Septic Tank, Vertical constructed wetland, Microfilter, Activated carbon filter, Softener, Ultrafiltration, Reverse osmosis, Ion exchange	Potable water	Belgium	Restaurant visited by 90-135 people per day	(Lakho et al., 2021)
Fermentation tank	Biogas	Germany	Urban community	(Schelbert, Luthi, & Binz, 2023)
Digester	Biogas	Germany	Urban community	(Sustainable Sanitation Alliance, 2009)
Upflow anaerobic sludge blanket reactor, struvite precipitation, dewatering, sludge pyrolysis	Biogas, Fertiliser, Phosphoric Acid, Co-treatment of effluent with greywater to generate process water for industry	Belgium	Urban community	(Run4Life, 2024)
Fermentation, Struvite precipitation	Biogas, Fertiliser	Sweden	Urban community	(Schelbert, Luthi, Binz, & Miorner, 2023)

Methods

3 Methods

3.1 Urban community

The first step was to define the characteristics of the hypothetical urban community. This involves specifying parameters, such as quality and quantity of blackwater generated, the reuse possibilities, space available, and effluent quality requirements.

Step 1 Urban Community	Step 2 Appropriate Technologies and Treatment Trains	Step 3 Static Modelling and Environmental Sustainability	Step 4 Feasibility Study

3.1.1 Land availability

The available land area for installing a treatment plant was estimated using Google Earth's polygon tool as shown in **Figure 4**. It was assumed that only 50% of the area measured using Google Earth would be available for construction of a treatment plant. Two residential communities, one in Dübendorf, Switzerland and another in Mumbai, India each accommodating ~2000 residents, were selected for calculation of available land area.

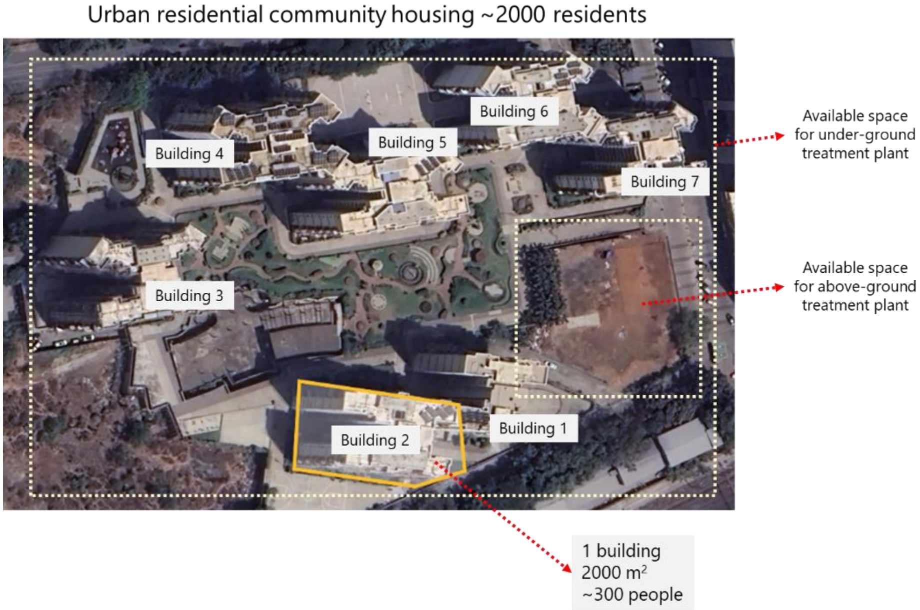


Figure 4: Google Earth view of a residential community in Mumbai, India housing 2000 residents. Polygon tool was used to measure the area occupied by one building (Building 2). This was scaled up to 7 buildings that were identified to be a part of the residential community. A potential site for installation of an above-ground treatment plant was also identified and is labelled. The space occupied by the residential community corresponds to the space available for an under-ground treatment plant as labelled.

3.1.2 Water quantity

Data on blackwater flow rates in the urban community was assumed to correspond to the flow rates in NEST. Data on blackwater flow rates in the NEST was collected by operating the existing dewatering unit (**Figure 1**) for 5 days between 26 February 2024 (9:00 AM) until 1 March 2024 (5:30 PM) for 24 hours each day. Blackwater flowed into the equalization tank and the water level was measured every second using a pressure sensor. When the recorded water level attained a value of 40 litres, the equalization tank was automatically emptied. This process was repeated throughout the indicated time period to obtain a time series of level changes in the equalization tank which was converted to flow rate in m^3/day. In this manner, the average, minimum and maximum flow rates were recorded. The data collected from the NEST was assumed to correspond to 30 residents and was scaled up for 2000 residents of the urban community. The NEST is a unique environment and therefore the scaling up of flow rates may not provide an accurate estimation of the flowrates. Therefore, the impact of scaling up these values on treatment system design was evaluated by means of an uncertainty analysis (**3.3.3 Uncertainty analysis**).

3.1.3 Water quality

Data on water quality in the urban community were assumed to correspond to that in NEST. Data on water quality of the blackwater, blackwater supernatant and screw press liquid (**Figure 1**) were collected by operating the existing dewatering unit at the NEST during the time slots summarized in **Table 2** to capture the variability across 24 hours. Laboratory triplicates were performed for certain samples to quantify the errors attributable to variability in blackwater composition.

Table 2: Sampling plan used for characterizing the blackwater, blackwater supernatant and the screw press liquid collected in the NEST building.

Date and day of sampling	Time Slot	Sampling point	Laboratory replicates	Measurement replicates
18-01-24 (Tue)	10.00 – 13.00	Blackwater	1	3
		Blackwater Supernatant	3	1
		Screw Press Liquid	1	3
24-01-24 (Wed) to 25-01-24 (Thu)	18.00 – 5.00	Blackwater	1	1
		Blackwater Supernatant	1	1
		Screw Press Liquid	3	1
25-01-24 (Thu)	6.00 – 9.30	Blackwater	1	1
		Blackwater Supernatant	1	1
		Screw Press Liquid	1	1
29-01-24 (Mon)	8.00 – 10.00	Blackwater	1	1
		Blackwater Supernatant	1	1
		Screw Press Liquid	1	1
5-02-2024 (Mon)	10.00 – 13.00	Blackwater	1	1
		Blackwater Supernatant	3	1
		Screw Press Liquid	1	1

Between the indicated time slots, the blackwater was collected in the equalization tank. The composite sample at the end of a time slot was homogenized using a pump. Subsequently poly-acrylamide based flocculant, CP314 0.5% was dosed in the flocculation tank. This flocculant was selected due to its proven effectiveness in handling highly variable influent blackwater characteristics (Shaw et al., 2022). In addition, it forms strong flocs, that are essential for withstanding shear stresses in the screw press, thereby preventing floc breakup and escape of solids into the screw press liquid (Shaw et al., 2022). The dosage of flocculant was determined automatically based on the concentration of suspended solids recorded by a total suspended solids sensor (Endress + Hauser CUS50D). After two minutes of flocculation and settling, the screw press was operated where the solids were further separated from the liquid.

After each trial 500 mL of raw blackwater, the blackwater supernatant and the screw press liquid were sampled and stored at 4°C before being analyzed for 14 water quality parameters. These parameters were essential to perform desk-based wastewater treatment system design as recommended by

Tchobanoglous et al. (2013). These parameters include: Total suspended solids (TSS), Total solids (TS), Volatile suspended solids (VSS), Turbidity, Alkalinity, Chemical Oxygen Demand (COD), Soluble Chemical Oxygen Demand (sCOD), Biochemical Oxygen Demand (BOD_5), Ammonia-Nitrogen (NH_4-N), Total Kjeldahl Nitrogen (TKN), Phosphate-Phosphorous (PO_4-P), Total Phosphorous (TP), Conductivity (EC), and pH. Measurements were performed by other researchers at Eawag using standard methods described elsewhere (Velkushanova et al., 2021b; Verloo, 2022).

The concentrations recorded from lab analysis were converted into flow-weighted concentrations using **Equation 1**. Flow weighted concentrations were used to develop static design as they are a more accurate representation of the actual wastewater strength that must be treated (Tchobanoglous et al., 2013).

$$C_w = \frac{\sum_{i=1}^{n} q_i C_i}{\sum_{i=1}^{n} q_i}$$

Equation 1

where,

C_w = flow weighted average constituent concentration

n = number of observations

q_i = average flow rate during the i^{th} time period

C_i = average concentration of the constituent during the i^{th} time period

3.1.4 Reuse possibilities and effluent quality requirements

The reuse possibilities for blackwater effluent were grouped into three categories. Three categories of reuse (e.g., unrestricted public access) were defined instead of defining three specific reuse application (e.g., toilet flushing) because of two reasons:

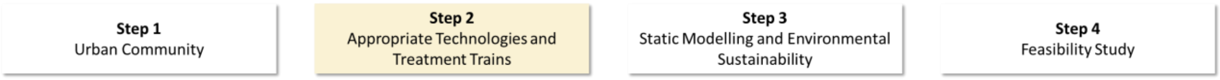
- It was a more practical approach because the designed treatment system could be used for reclaiming blackwater in several applications rather than only one
- The effluent compliance values set by regulatory bodies are often defined for reuse categories rather than specific reuse application. For example, the ISO 30500:2018 standard (ISO, 2018) specifies effluent standards for *Category A: Unrestricted Urban Uses* instead of specifying them for, say, fire-fighting.

Several limitations associated with defining reuse categories instead of specific reuse application were identified and they are enumerated in **4.1.3 Reuse possibilities and effluent quality requirements**.

The three categories of reuse and corresponding effluent quality requirements were defined based on *Guidelines for Water Reuse* (US EPA, 2012), and *Non-sewered sanitation systems - Prefabricated integrated treatment units - General safety and performance requirements for design and testing* (ISO, 2018). These standards were selected because of their global applicability, focus on water reuse, and applicability to non-sewered sanitation systems, especially, ISO (2018).

3.2 Appropriate technologies and treatment trains

Having defined the characteristics of the urban community, the second step was to select appropriate technologies for the given context using pre-selection criteria. Once appropriate technologies are selected, they are configured into treatment trains. Since several treatment trains were capable of achieving the specified effluent targets, decision-making criteria were defined to compare these treatment trains and select one.



3.2.1 Pre-selection

Currently, the blackwater reclamation unit comprises an equalization tank, a flocculation tank, and a screw press. These units together provide primary treatment. The liquid output from the screw press requires further treatment through secondary, tertiary, and advanced processes before it can be reused since it contains high levels of nutrients and pathogens (Anusuyadevi et al., 2023). While academic textbooks and scientific literature offers a list of established and emerging technologies for all levels of treatment, not all technologies are suitable for the specific needs of the urban community considered in this thesis.

To identify the most appropriate technologies, a two-step process was utilised to produce a final shortlist of 17 technology options presented in **4.2 Appropriate technologies and treatment trains**. First, a long list of technologies was compiled from a review of textbooks and literature. The review focused on identifying technologies previously applied in non-sewered, decentralized, semi-centralized, on-site, or off-grid treatment plants. Second, the identified technologies were grouped together using the pre-selection criteria given below and organized into a pre-selection matrix (**4.2.1 Pre-selection**).

Using the pre-selection matrix, a final shortlist of the 17 options was developed (**4.2.1 Pre-selection**). While these 17 options were specifically suited for blackwater reclamation in the hypothetical urban community considered in this thesis, the pre-selection matrix (**Table 6**) can be used by anyone to come up with a unique list of appropriate technologies.

The following pre-selection criteria were defined:

- **Location.** This criterion assesses whether the technology can be installed underground or above-ground. It was chosen because the space available for installation of a treatment plant varies based on location. Public acceptance also differs depending on whether the plant is above or underground (NITI Aayog & Atal Innovation Mission, 2022).
- **Nutrient Removal.** This criterion evaluates the degree of nutrient removal that can be achieved using a particular technology. It was selected due to adoption of stricter nutrient removal targets to protect the environment and public health globally, and especially in high-income countries (US EPA, 2012). The degree of nutrient removal that could be achieved was determined by reviewing textbooks (Asano et al., 2007; Tchobanoglous et al., 2013), review papers (Rout et al., 2021; Ugwuanyi et al., 2024), and technical reports (Brault et al., 2022a).
- **Scale.** This criterion defines the cost-effectiveness of the technology at various scales. It was chosen because some technologies, such as electro-mechanical units, become disproportionately expensive to purchase, operate, and maintain as they get smaller (Brault et al., 2022a). The ability to downscale cost-effectively was determined by reviewing textbooks (Asano et al., 2007; Tchobanoglous et al., 2013) and technical reports (Brault et al., 2022a) and confirming previous applications in at least five full-scale decentralized, semi-centralized, on-site, or off-grid treatment plants using review papers and technical reports (Diaz-Elsayed et al., 2019; Guo et al., 2014; N. K. Singh et al., 2015).

- **Application.** This criterion assesses whether the technology has been previously applied in treatment plants of similar capacity and urban communities with characteristics comparable to the one considered in this thesis. It was selected based on the assumption that proven success in similar contexts ensures sufficient operational expertise for troubleshooting, which is crucial for public acceptance of blackwater reuse and non-sewered sanitation. Pilot plants must demonstrate successful results to validate non-sewered sanitation as a viable complement to sewered systems. Emerging or innovative technologies are also indicated in the pre-selection matrix for consideration by future researchers, although the primary focus in this thesis is selecting off-the-shelf technologies.

3.2.2 Configuring treatment trains

The pre-selected technologies from the previous step are configured into treatment trains such that the full treatment train meets the log reduction target for different pathogens (e.g., bacteria, viruses, helminths, protozoa) specified by the effluent quality standards. **Appendix 2** presents the log reduction of pathogens that can be achieved with various technologies. Additional technologies were added to the treatment train if required to meet the nutrient, COD or TSS targets that the effluent must comply with.

3.2.3 Decision-making criteria

The previous step yields several acceptable treatment trains however only one treatment train would be implemented in the urban community. Therefore, decision-making criteria were adopted to narrow them down to one treatment train per reuse category. These criteria were derived from referenced studies (Spiller, 2016; Wingelaar, 2023).

Wingelaar (2023) reviewed 101 articles to develop a list of 20 criteria for comparing sanitation options in Philippines for his master's thesis at Delft University of Technology, Netherlands while Spiller (2016) provided a list of 73 indicators to compare urban sanitation concepts. Comparing the two studies, all criteria from Wingelaar (2023) were included in Spiller (2016) and therefore the list developed by Spiller (2016) was considered further.

To ensure an accurate comparison of treatment options, the decision making criteria should be (Wingelaar, 2023):

- Widely accepted by the scientific community
- Transparent, i.e., their calculation and selection must be obvious even to non-experts
- Relevant to the specific context
- Quantifiable, i.e., they should be based on existing data or the data can be easily collected
- Limited in number

Since the decision-making criteria should be limited in number, 14 were selected from Spiller's list of 73 indicators following the process shown in **Figure 5** as described below.

- First, criteria irrelevant to the specific context were removed, such as, 'alignment with policy'. These criteria do not directly allow comparison of sanitation 'technologies' but instead focus on comparing the sanitation service chain. They were deemed irrelevant for this thesis where the focus is on comparing sanitation technologies.
- Second, criteria with similar definitions were merged. For instance, 'durability' and 'robustness' were combined due to their overlapping definitions—'durability' is the ability to withstand wear and tear, and 'robustness' echoes the same sentiment where it defines the system's capacity to remain operationally effective over its lifetime with minimal upkeep (Wingelaar, 2023).

The 14 selected decision-making criteria are presented in **4.2.3 Decision-making criteria**, with their definitions (definitions were adapted from Wingelaar (2023)). **Appendix 3** provides details on which indicators from Spiller's list were not selected and which were merged.

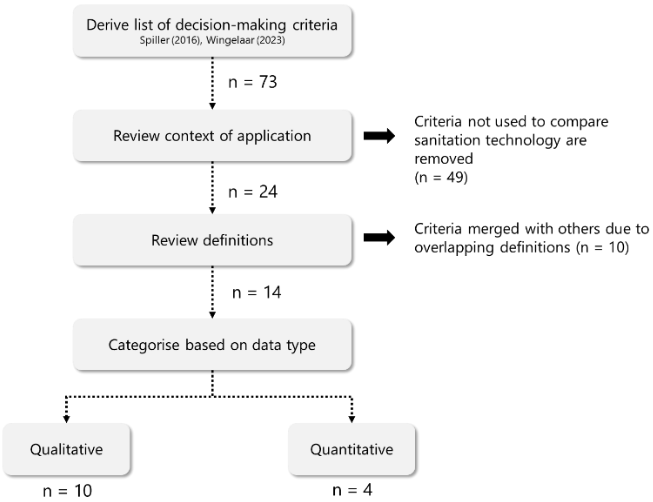


Figure 5: Flowchart depicting the process employed for selecting decision-making criteria.

3.2.4 Selecting one treatment train

The decision-making criteria defined in the previous step were used to compare treatment trains and select one treatment train for each reuse category. The decision-making process employed to make this comparison and selection is described below and represented schematically in **Figure 6**.

- **Qualitative Indicators.** Personal professional expertise, developed by reviewing key references, was used to rate treatment trains on qualitative indicators as 'high', 'medium', or 'low'. These ratings were then converted to numerical values: 1 for low, 2 for medium, and 3 for high, or the reverse, depending on whether a higher or lower score was preferable for a specific indicator. For example, a 'high' rating for 'reliability' is coded as 3, while a 'high' rating for 'level of expertise required' is coded as 1. The following resources were reviewed to develop this expertise: Tare & Bose (2009), Tchobanoglous et al. (2013), and Frankel (2022). **Appendix 4** provides the text codes assigned to various technologies for different indicators.

  A disadvantage of this approach is that the values assigned for qualitative indicators were based on author's expertise and not verified using other means such as discussion with experts due to lack of resources and time. Inspite of outreach efforts via Reddit, LinkedIn, Emails and WhatsApp, it was difficult to connect with operators who had experience with maintaining non-sewered treatment plants and could cross-verify the values assigned for qualitative indicators. Other researchers referring to this thesis can employ other/better data collection methods (e.g., interviews with users and experts) to assign values for qualitative indicators for a specific context and urban community following the method described by Wingelaar (2023).
- **Quantitative indicators.** Treatment trains were ranked on quantitative indicators using data derived from Tare & Bose (2009), Srivastava & Singh (2022), Chhipi-Shrestha et al. (2017), Brault et al. (2022a), and Tchobanoglous et al. (2013). Refer to **Appendix 5** for the quantitative data derived for various technologies.
- **Normalisation and Aggregation.** To compare the treatment trains across indicators, values were normalized to a scale of 0 to 1 using **Equation 2** (Firmansyah et al., 2021). The normalized values for each treatment train were then summed up, and the train with the lowest total score was selected for further consideration.

A matrix of the normalized scores for all treatment trains, along with further discussions, are presented in **4.2.4 Selecting one treatment train**.

$$\text{Normalised value of indicator for selected treatment train} = \frac{\text{Actual value for selected treatment train} - \text{Minimum from all treatment trains}}{\text{Maximum from all treatment trains} - \text{Minimum from all treatment trains}}$$

Equation 2

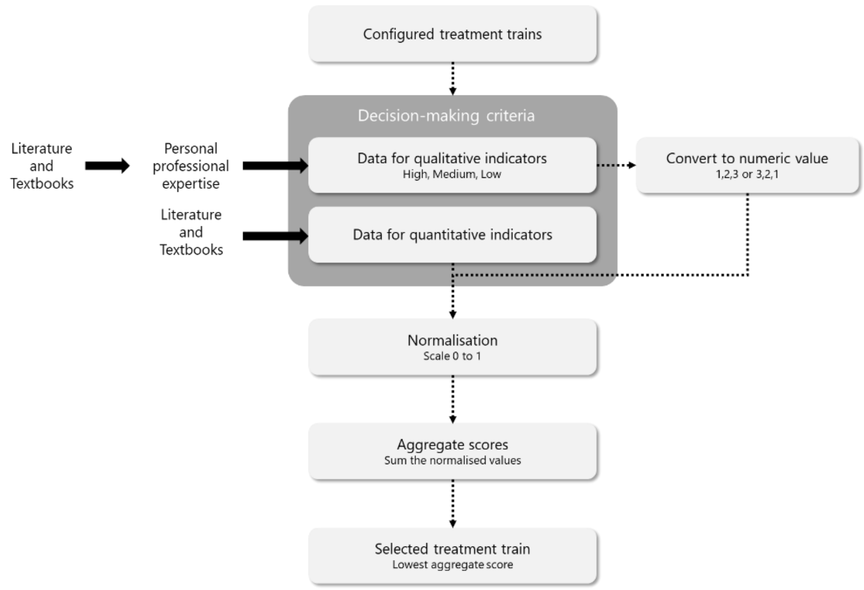
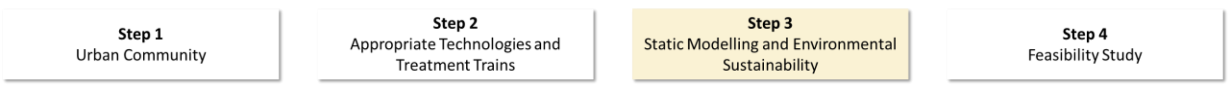


Figure 6: Flowchart depicting the process employed for selecting a treatment train for each defined reuse possibility.

3.3 Static modelling and environmental sustainability

After selecting one treatment train for each reuse category from the previous step, the next step was to perform unit sizing and conduct an uncertainty analysis. The results from these analyses were used to select one reuse category (from the three defined in Step 1) for future implementation in the urban community. Additionally, the environmental sustainability of a complete non-sewered sanitation system using a carbon footprint analysis was evaluated to generate insights on benefits and trade-offs of a non-sewered sanitation approach.



3.3.1 Static modelling

Unit sizing for the secondary treatment processes was performed using static modeling in BioWin 6.2, a globally used simulator developed by EnviroSim for the analysis and design of municipal wastewater treatment plants (EnviroSim Associates Limited, 2024). Input water quality characteristics were derived from **3.1.3 Water quality**, while the wastewater fractions, reaction rates, and microbial growth constants were assumed as BioWin default values. Preliminary calculations were conducted using MS Excel and engineering concepts from Tchobanoglous et al. (2013).

Unit sizes for tertiary and advanced treatment processes were manually calculated using the theory from Tchobanoglous et al. (2013). Membrane processes were simulated in WAVE software to estimate chemical requirements for membrane cleaning and approximate energy consumption. WAVE, developed by DuPont Water Solutions, is a free modeling software for simulating ultrafiltration, reverse osmosis, ion exchange, and other membrane-based processes (DuPont Water Treatment Solutions, 2024).

The theory and equations from Tchobanoglous et al. (2013) used to perform unit-sizing calculations for various processes are presented in **Appendix 6**.

3.3.2 Selecting one reuse category

Unit sizing calculations in the previous step were performed for treatment trains designed for all reuse categories. However, due to practical constraints, only one reuse category would be pilot tested in the urban community (and the NEST building). To select this reuse category, informal interviews were conducted with experts from Eawag and Consortium for DEWATS Dissemination India (CDD India, 2024). Details about these experts are presented below.

- Michael Vogel, is a project officer at Eawag and is responsible for developing and testing technologies for blackwater treatment and reuse in NEST. He is working along with Linda Strande, the head of the MEWS group.
- Giuseppe Congiu, a project engineer at Eawag with an environmental engineering background, has experience with operating the greywater treatment system installed in the NEST.
- David Hasler, a mechanical engineer at Eawag, has experience with designing prototypes and pilot scale units. He is involved with designing and testing the blackwater dewatering currently being pilot tested in the NEST.
- Rohini Pradeep, is a project manager at CDD Society in India and comes from an environmental engineering background. She has 15 year experience in design and implementation of decentralised wastewater treatment in India.
- Eberhard Morgenroth, is the head of process engineering department at Eawag and is leading the development and testing of greywater treatment unit currently being pilot tested in the NEST and as a part of developing technologies for non-sewered sanitation.

Some experts were asked the following open-ended questions to guide discussions:

- Which reuse possibility would you pilot test in a hypothetical urban community and in the NEST? Why?
- What design parameters (e.g., costs, energy consumption, compliance etc.) affect your decision to select a technology?
- What are some common issue that you encounter while operating a non-sewered system?
- In your experience, are urine separating systems popular among users? If not, why?
- How difficult or easy it is procure and handle chemicals if they are needed in your opinion? What are some problems that will be most likely encountered?
- Out of UV and Chlorination, which disinfection technology would you prefer?

3.3.3 Uncertainty analysis

The design output generated in **3.3.1 Static modelling** was produced under various assumptions, neglecting the variability in design input. To quantify the effect of this variability, an uncertainty analysis was conducted (Geffray et al., 2019). Input parameters that affect the design output were first identified as follows:

- **Co-treatment of greywater and blackwater.** It was assumed that blackwater and greywater are collected separately. This assumption is valid for residential communities under-construction since installing source-separating piping in buildings that are already constructed would be too cost-prohibitive. However, for residential communities that do not have source-separating pipelines but where the users desire to practice wastewater reuse, the design output from **3.3.1 Static modelling** may not apply. Hence, the impact of co-treating greywater and blackwater was assessed.

- **Degree of urine separation.** Another assumption was that some toilets divert urine while others do not. It was hypothesized that higher urine diversion could lead to better nutrient removal, given that 70% of nitrogen and 50% of phosphorous in domestic wastewater is contained in urine (Reynaert et al., 2020b). Therefore, the effect of no urine separation and complete urine separation on design output was evaluated.
- **Blackwater supernatant treatment.** The input water quality considered for unit sizing in **3.3.1 Static modelling** was based on the water quality of the screw press liquid. However, it is possible that the quality of the screw press liquid is inferior to the quality of the blackwater supernatant (Figure 1, page 11) due to the breaking up of flocs in the screw press attributable to shear forces (Shaw et al., 2022). Therefore, the advantage or disadvantage of treating the blackwater supernatant instead of the screw press liquid was evaluated.
- **Worst efficiency of the screw press.** Design calculations in **3.3.1 Static modelling** were based on the assumption that the input water quality is equivalent to flow-weighted average concentrations calculated using **Equation 1**. However, the input water quality concentrations can vary due to fluctuations in the efficiency of primary treatment (flocculation tank and screw press), influenced by factors such as the type of flocculant used and operational practices. Consequently, the impact of the worst-performing efficiency of primary treatment on downstream system design was evaluated.
- **Low and high flow conditions.** Design calculations in **3.3.1 Static modelling** were based on average flow conditions scaled up from the NEST building. However, unit sizing may vary under high and low flow conditions, necessitating an assessment to determine the need for an equalization tank.
- **Flow conditions in other communities.** Flow rates in the NEST building, while scaled up for design calculations in **3.3.1 Static modelling**. However, these flowrates may not accurately represent typical urban communities. This is because the NEST is a unique urban community with multiple visitor entering the building throughout the day, and varying occupancy levels due to the presence of offices in addition to residential units. A purely residential community may have higher or lower production of blackwater. Therefore, minimum and maximum flow rates recorded in different urban communities worldwide were collected and averaged from referenced studies (Roshan & Kumar, 2020; Tchobanoglous et al., 2013; Welling et al., 2020) and were used to understand the variability in design output.

Uncertainty analysis was conducted only for the secondary treatment unit corresponding to the reuse category selected in **3.3.2Selecting one reu se category**. The method used to derive input water quality to the secondary treatment unit for each scenario of the uncertainty analysis is detailed in **Appendix 7**.

3.3.4 Carbon footprint analysis

The GHG emissions for the proposed non-sewered sanitation system were calculated using the emission factor approach established by the Intergovernmental Panel on Climate Change (IPCC), as applied in the referenced study (X. Zhou et al., 2022). Greenhouse gases methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) are emitted during wastewater treatment. These emissions can be categorized into direct (Scope 1) and indirect emissions (Scope 2 and Scope 3) as described below.

- **Scope 1 CH_4 emission.** These emissions occur due to anaerobic conditions during transport in pipelines, and during treatment stages (aerated grit chambers, primary settling tanks, and equalisation tanks) (Bartram et al., 2019).
- **Scope 1 N_2O emission.** These emissions occur during nitrification and denitrification. Factors such as operational conditions, selection of nitrogen removal processes, nitrogen loading rates, and levels of dissolved oxygen can influence N_2O emissions (Foley et al., 2010).

- **Scope 1 CO_2 emission.** These emissions result from the biological degradation of organic matter during treatment stages. However, these emissions are part of the natural carbon cycle and are not considered in carbon footprint calculations (X. Zhou et al., 2022).
- **Scope 2 CO_2 emission.** These emissions arise from purchase and use of electricity within the treatment plant (e.g., aeration, pumps) and along the service chain (e.g., transport) (Bartram et al., 2019).
- **Scope 3 emission.** These emissions stem from activities not directly occurring at wastewater treatment facilities but indirectly contributing to emissions. These include the production of chemicals and materials or the transportation of resources to treatment facilities (Bartram et al., 2019). In this thesis, emissions from the production of chemicals and technologies are considered, while other Scope 3 emissions are excluded (e.g., due to transport), as this analysis represents a generic rather than site-specific carbon footprint calculation.

The carbon footprint of the blackwater reuse unit designed for Reuse Category 1 and 2 applications (**4.1.3 Reuse possibilities and effluent quality requirements**) for the urban community was calculated. This system includes a moving bed biofilm reactor, chemical precipitation for phosphorous removal, ultrafiltration, granular activated carbon, and UV disinfection unit as determined in **4.2.4 Selecting one treatment train**.

Additionally, the carbon footprint of a complete non-sewered sanitation system, which encompasses separate treatment units for brownwater (assuming 90% urine separation), greywater, and urine, was also evaluated. The specific unit sizing for the greywater and urine treatment systems was not within the scope of this thesis. It was assumed that greywater treatment would be accomplished using a moving bed biofilm reactor, ultrafiltration, and chlorination processes, similar to that existing in the NEST. Urine treatment would be achieved using a decentralized urine fertilizer production system that includes: urea hydrolysis, partial nitrification, pharmaceutical removal, and distillation. The emission factors and design of this urine treatment system were assumed to be based on the existing system in NEST (Faust et al., 2022).

The components included in the carbon footprint analysis are presented in **Figure 7**. Data for emission factors was derived from various sources as given below. The reader is referred to **Appendix 8** for full dataset of emission factors used in this study.

- Emission factors for direct emissions of CH_4 and N_2O were derived from X. Zhou et al. (2022) because this was the only study that reported emission factors for the selected technologies.
- The emission factors for electricity consumption in different countries were derived from secondary sources (Romano, 2019; Tsukui et al., 2024b; U.S. Energy Information Administration, 2024).
- The emissions associated with the production of chemicals and technologies, expressed in kilograms of CO_2-equivalent (kgCO_2-eq), were derived from the Ecoinvent 3.10 database (Ecoinvent, 2024). Ecoinvent is a repository that includes over 20,000 datasets modelling various human activities and industrial processes (Ecoinvent, 2024). One of the key sustainability indicators measured within this database is the global warming potential of human activities and industrial processes, which is quantified in terms of equivalent kilograms of CO_2 emitted (Ecoinvent, 2024). This metric allows for the assessment of the environmental impact of different activities and processes by providing a standardized measure of their contributions to global warming.

Carbon footprint was calculated only for the treatment train corresponding to the selected reuse category (**3.3.2 Selecting one reuse category**). In this thesis, emissions saved, e.g., emissions saved due to reduction in extraction of freshwater for toilet flushing were not included in the calculations. However, these emissions will be important when comparing the non-sewered system to other non-sewered or sewered treatment systems and should be quantified by future researchers.

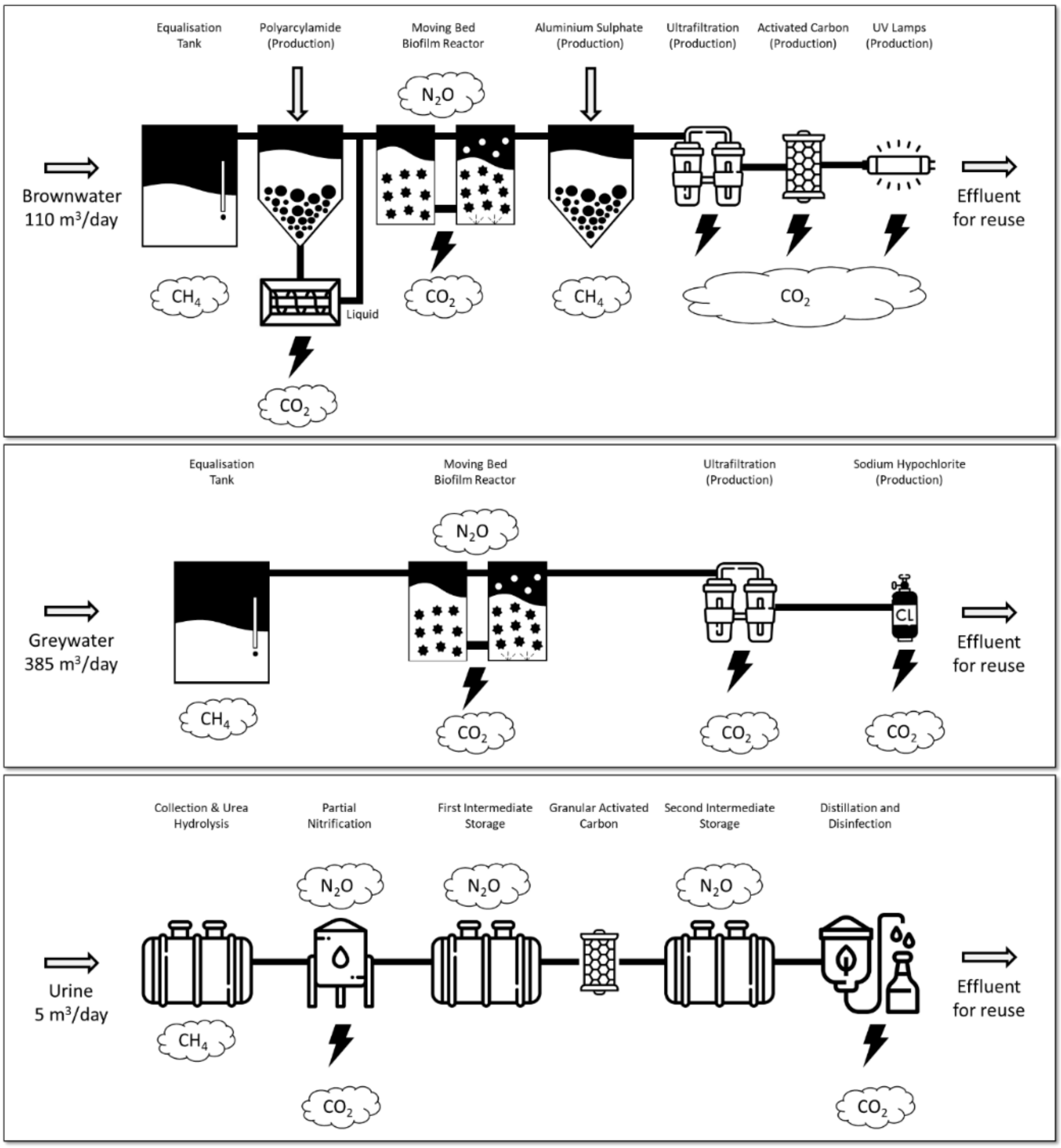


Figure 7: Schematic representing unit processes included in the calculations of the carbon footprint of a non-sewered sanitation system.

The emission factor were utilized to calculate the greenhouse gas emissions according to the following equations (X. Zhou et al., 2022). The direct CH_4 emission in carbon dioxide equivalents were calculated using **Equation 3**, the direct N_2O emissions were calculated using **Equation 4**, the indirect CO_2 emissions from electricity consumption were calculated using **Equation 5**, and the indirect CO_2 emissions from production of materials and chemicals were calculated using **Equation 6**.

$$CO_2 - eq\ (CH_4) = Q\ \times (COD_{in} - COD_{eff}) \times EF_{CH4} \times GWP\ (CH_4)$$

Equation 3

$$CO_2 - eq\ (N_2O) = Q\ \times (TN_{in} - TN_{eff}) \times EF_{N_2O} \times GWP\ (N_2O)$$

Equation 4

$$CO_2 = W \times EF_{Electricity}$$

Equation 5

$$CO_2(Production) = Quantity\ of\ product\ \times GWP\ (CO_2)$$

Equation 6

where,

Q	= wastewater flowrate in m^3/year
COD_{in}, COD_{eff}	= average COD concentration of the influent and effluent in kg COD/m^3
TN_{in}, TN_{eff}	= average COD concentration of the influent and effluent in kg TN/m^3
EF_{CH4}	= emission factor for CH_4 for the treatment process in kg CH_4/kg COD
EF_{N2O}	= emission factor for N_2O for the treatment process in kg N_2O/kg TN
GWP (CH_4)	= Global warming potential with a 100-year horizon of CH_4, used to convert CH_4 emissions to carbon dioxide equivalent units = 28
GWP (N_2O)	= Global warming potential with a 100-year horizon of N_2O, used to convert N_2O emissions to carbon dioxide equivalent units = 265
GWP (CO_2)	= Global warming potential of producing 1 kg of product derived from Ecoinvent 3.10 database in kgCO_2-eq
W	= annual electricity consumption in kWh
$EF_{electricity}$	= Composite electricity/heat emission factors in kg CO_2-eq/kWh

3.4 Feasibility study

The final part of the thesis focuses on evaluating the applicability of the results and methods developed for the hypothetical urban community to the NEST building (a wastewater research facility) and to other urban communities in low-, middle-, or high-income countries. This involves a detailed discussion of the adaptability and scalability of the proposed system.

In addition, modifications were made to the theoretical designs developed in **3.3 Static modelling and environmental sustainability** to adapt it for pilot testing by future researchers in the NEST. The proposed process design is conveyed through a piping and instrumentation diagram created using PowerPoint. This diagram provides a visual representation of the proposed system layout and equipment arrangement, facilitating a clearer understanding of the design.

Results and Discussions

4 Results and Discussions

4.1 Urban community

The first step was to define the characteristics of the hypothetical urban community. This involves specifying parameters, such as quality and quantity of blackwater generated, the reuse possibilities, space available, and effluent quality requirements.

4.1.1 Land availability and water quantity

The urban community is characterized by the following features: It has a population of 2,000 residents living in 6-8 buildings, covering an area of 20,000-30,000 m². An above-ground treatment plant could be allocated 1,500-2,000 m², while an underground unit could occupy and area of 10,000-15,000 m² (**3.1.1 Land availability**).

The community records an average production of ~100 m^3/day of blackwater. Assuming an infiltration of 10%, a design value of 110 m^3/day was used to develop conceptual designs in **4.3 Static modelling and environmental sustainability**. The highest instantaneous flow rate observed was ~600 m^3/day which lasted for 6 minutes (between 11:08 and 11:14) whereas the lowest flow was ~6 m^3/day (lasting 6 hours between 00:00 and 07:00). These are scaled up flow rates from NEST and the full dataset of flow rates recorded in the NEST is presented in **Appendix 9**. The large range of flow rates recorded emphasise the importance of an equalization tank (which is already an integral part of the primary treatment for the urban community as shown in **Figure 1**). An equalization tank would also prevent under- and overloading of the treatment plant, a common issue for non-sewered plants due to the variability of wastewater generation throughout the day (Vijayan et al., 2023). Thus, the flow rates and available area in the urban community were recorded, motivating the choice of an equalization tank.

The description of an urban community presented above aligns with the definition of a 'medium-scale satellite system' (Angelakis et al., 2018) or a 'small-town' (Brault et al., 2022b). The wastewater flow rates typically observed in such a community range from 20 – 5000 m^3/day. This definition is utilized in **4.2 Appropriate technologies and treatment trains** to select technologies appropriate for application at this scale.

Flow rates in the NEST building, while scaled up for design purposes, may not accurately represent typical urban communities. This is because the NEST is a unique urban community with multiple visitor entering the building throughout the day, and varying occupancy levels due to the presence of offices in addition to residential units. A purely residential community may have higher or lower production of blackwater. This assumption was tested in an uncertainty analysis (**4.3.3 Uncertainty analysis**).

4.1.2 Water quality

The results of water quality analysis are presented in **Table 3.** The characteristic of domestic wastewater and blackwater derived from literature are also indicated for reference. Blackwater composition is more variable as compared to domestic wastewater due to several reasons such as flush water consumption, dietary habits, age, height, and living standards (Rose et al., 2015; Shaw et al., 2022).

Table 3: Composition of blackwater, blackwater supernatant and screw press liquid collected in the NEST building. Blackwater supernatant represents the composition of the liquid from the flocculation tank after flocculation and settling. Screw press liquid represents the composition of the liquid left after flocculation and dewatering in the screw press. The composition of blackwater and domestic wastewater derived from literature are indicated for reference. TSS=Total suspended solids, TS=Total solids, COD=Chemical oxygen demand, sCOD = Soluble chemical oxygen demand, BOD_5=5 day biochemical oxygen demand, NH_4-N=Ammonia nitrogen, TN=Total nitrogen, TP=Total phosphorous, EC=Electrical conductivity.

Parameter	**Unit**	**Raw Blackwater**	**Blackwater Supernatant**	**Screw Press Liquid**	**Blackwater** (Zhang et al., 2023)	**Domestic wastewater** (Tchobanoglous et al., 2013)
TSS	mg/L	1180 - 2840	110 – 720	140 – 1190	46 – 1030	130 - 389
TS	mg/L	1740 - 3120	560 – 1560	700 – 1890	920 – 4320	537 - 1612
Turbidity	NTU	247 – 2045	155 – 681	130 – 850	100 – 600	-
Alkalinity	mmol HCO_3/L	-	-	8.5 – 15	-	-
COD	mg/L	1924 – 4119	390 – 1904	680 – 2368	260 – 8700	339 – 1016
sCOD	mg/L	261 – 688	235 – 784	234 – 765	400 – 3050	-
BOD_5	mg/L	-	-	150 - 250	182 – 1400	133 – 400
NH_4-N	mgN/L	28 – 156	27 – 120	25 – 123	80 – 1240	14 – 41
TN	mgN/L	110 - 270	82 – 241	88 – 234	49 – 1750	23 – 69
PO_4-P	mgP/L	10 – 21	9 – 19	9.5 – 16.5	-	-
TP	mgP/L	25 – 45	11 – 39	13 – 40	8 – 202	3.7 – 11
EC	microS/cm	803 – 1736	930 – 1530	787 – 1529	-	-
pH	pH	8 – 9	8 – 9	8 – 9	7 – 9	-

As compared to domestic wastewater the screw press liquid is two times more concentrated for COD and TSS, whereas it is four times more concentrated for TN and TP. This is because domestic wastewater is diluted due to the presence of greywater which has lower organic content when compared with blackwater. In addition, only some toilets in the urban community were assumed to be urine separating toilets. This explains the high concentration of TN and TP as urine consist of 85–90% of nitrogen, and 50–80% of phosphorus in domestic wastewater (Sohn et al., 2023). The high variability in the blackwater composition reported in literature is because certain studies report the blackwater composition from vacuum toilets where flush water consumption is 0.5-1 L as opposed to 5-7 L in conventional dual flush toilets (Oarga Mulec et al., 2016). Therefore, the technology selection in **4.2 Appropriate technologies and treatment trains** should prioritize technologies that are resilient to inflow variability and capable of achieving high nutrient removal.

An escape of solids from the screw press into the screw press liquid was also observed. The flocculant used, CP314, forms strong flocs (Shaw et al., 2022). However, the solids escape may be because the flocculant dose was optimized for high settling performance rather than for forming strong flocs. The shear stress from the screw press's rotating action can cause the flocs to break up. With weaker flocs, a higher escape of solids occurs, leading to poor removal of TSS and COD (Shaw et al., 2022). Therefore, it is crucial to optimize the flocculant dose not only for settling performance but also for the strength of the flocs to ensure that downstream treatment units function efficiently.

The sCOD/COD ratio for the blackwater is 0.13, which is lower as compared to domestic wastewater (0.32) and blackwater from literature (0.31) (Hocaoglu et al., 2010). This indicates that the blackwater from NEST has a higher particulate COD fraction. The high particulate fraction and the lower sCOD/COD ratio could be due to the presence of toilet paper and wet pipes in the blackwater, as observed in-person when samples were collected. Literature values reported in **Table 3** are averages from wastewater collected in ten different countries, where toilet paper usage varies which could be why they have lower particulate fraction. Higher particulate fraction will impact denitrification performance in secondary treatment because denitrifying organisms require readily degradable soluble COD for efficient denitrification (Tchobanoglous et al., 2013). The higher particulate fraction can also lead to pump failures. Therefore, system design and implementation should consider the impact of higher particulate fractions in NEST blackwater.

The COD removal due to flocculation and settling (from raw blackwater to blackwater supernatant) averaged 60%. This is comparable to the results observed by Shaw et al. (2022) (55%), and Kozminykh et al. (2015) (60%). In both studies, the blackwater was reported to have an sCOD/COD ratio of 0.3. These findings indicate that the flocculant CP314 is effective even at higher fractions of particulate COD, which is advantageous given the high variability in blackwater composition.

The average percent removal of TN and TP from primary treatment (equalisation tank, flocculation, settling, and screw press) is 7% for TN and 35% for TP. The ISO standard requires 70% TN removal and 80% TP removal for the complete non-sewered sanitation system. Thus, nutrient removal in primary treatment units reduces the removal that downstream treatment units must achieve. The average concentrations of TS and TSS are 2.83 g/L and 2.18 g/L, indicating low particulate TN and TP fractions in the blackwater (since TS is approximately the same as TSS). This explains the low TN removal, as 52% of influent TN is in the form of NH_4-N, contributing to soluble TN rather than particulate TN (Shaw et al., 2022). Additionally, 45% of TP is in the form of PO_4-P, contributing to the soluble fraction of TP. Therefore, primary treatment effectively removes the particulate fractions of TN and TP, while the soluble fractions need to be addressed by secondary, tertiary or advanced treatment units.

While only the PAM-based synthetic flocculant CP314 was used in this study, bio-based flocculants could also be considered, especially if the reuse of solids for applications such as composting is desired. Bio-based conditioners, like chitosan, can be locally sourced from chitin (Shaw et al., 2022). A previous study has demonstrated that bio-based flocculants (chitosan, Emfloc, and Tanfloc) are as effective for blackwater flocculation and settling as synthetic flocculants CP314 and SFC100 (Shaw et al., 2022). However, the resistance to shear stress is lower for flocs formed with bio-based flocculants (Shaw et al., 2022), which can lead to a higher escape of solids from the screw press. The referenced study did not evaluate the impact of shear stress on the breakup of different flocs. Therefore, further research is needed to assess the efficiency of bio-based flocculants for primary treatment of blackwater, including mechanical dewatering.

Thus, the blackwater, supernatant, and screw press liquid from the NEST were characterized. The concentrations were converted to flow-weighted concentrations (**3.1.3 Water quality**), and the average values were used for unit sizing in **4.3.1 Static modelling**. The significance of constituent concentrations and the importance of floc resistance to shear stress for blackwater reclamation was highlighted.

4.1.3 Reuse possibilities and effluent quality requirements

As mentioned in the **3.1.4 Reuse possibilities and effluent quality requirements**, three categories of reuse applications were defined based on restriction to public access. The definition of reuse categories, examples of specific reuse options in each category, and the effluent compliance targets are presented in **Table 4**. The definitions, examples, and compliance targets were derived from referenced studies (Friedler et al., 2006; ISO, 2018; US EPA, 2012).

Compliance targets relevant to unit sizing are included here whereas full targets including those for noise, odour, metals or trace contaminants can be found in *Non-sewered sanitation systems - Prefabricated integrated treatment units - General safety and performance requirements for design and testing* (ISO, 2018), *The WHO Guidelines for Drinking Water Quality* (WHO, 2017) and the *National Primary Drinking Water Regulations of the US Environmental Protection Agency* (US EPA, 2024).

Table 4: Three categories of reuse applications were defined according to US EPA (2012) *and* ISO (2018)*. Examples of reuse options included under each reuse category are reported along with the effluent compliance targets. Only effluent compliance targets relevant for system design are reported. Full targets can be derived from Non-sewered sanitation systems - Prefabricated integrated treatment units - General safety and performance requirements for design and testing* (ISO, 2018)*, The WHO Guidelines for Drinking Water Quality* (WHO, 2017) *and the National Primary Drinking Water Regulations of the US Environmental Protection Agency* (US EPA, 2024).

	Reuse Category 1: Restricted Public Access	**Reuse Category 2: Unrestricted Public Access**	**Reuse Category 3: Potable Reuse**
Definition	The use of reclaimed water for non-potable applications in settings where public access is controlled or restricted by physical or institutional barriers, such as fencing, advisory signage, or temporal access restriction	The use of reclaimed water for non-potable applications in settings where public access is not restricted. Full body contact is accidental.	The use of reclaied blackwater for applications in which potable quality water is required and where full body contact and ingestion is regular and intended.
Examples of reuse applications	Silvilculture Aesthetic or storage ponds Sub-surface irrigation of non-edible crops Cooling towers Packaged air conditioners Surface water discharge	Fire-fighting Toilet flushing Vehicle washing Street washing Landscape irrigation Lakes used for boating Surface irrigation of non-edible crops Dust control Washing on construction sites Surface irrigation of constructed wetlands	Cooking Bathing Hand-washing Anal cleansing Showers Lakes used for swimming Irrigation of edible crops Cooling of food products Planned indirect potable reuse Direct potable reuse
Effluent Compliance Targets	TSS <= 30 mg/L COD <= 150 mg/L TN = 70% removal TP = 80% removal Bacteria, E. coli >= 6 LRV	TSS <= 10 mg/L COD <= 50 mg/L TN = 70% removal TP = 80% removal Bacteria, E. coli >= 6 LRV	Nitrite <= 1 mg/L Nitrate <= 10 mg/L TDS <= 500 mg/L Turbidity <= 2 NTU Bacteria, E. coli >= 7 LRV

	Virus, MS2 Coliphage >= 7 LRV Helminths, Ascaris sum >= 4 LRV Protozoa, Clostridium perfringens spores >= 6 LRV	Virus, MS2 Coliphage >= 7 LRV Helminths, Ascaris sum >= 4 LRV Protozoa, Clostridium perfringens spores >= 6 LRV	Virus, MS2 Coliphage >= 7 LRV Helminths, Ascaris sum >= 7 LRV Protozoa, Clostridium perfringens spores >= 7 LRV

Although reuse categories were defined for the urban community instead of defining specific reuse applications, due to the lack of availability of a better approach, several limitations and considerations associated with this method were identified. These are enumerated in the following paragraphs.

First, specifying compliance targets based on reuse categories rather than specific reuse applications could lead to oversimplification of system design and increase the risks associated with contact to reclaimed water (Reynaert et al., 2020a). For instance, grouping landscape irrigation and surface irrigation of wetlands under the same category (Reuse Category 2) neglects the different contact pathways associated with each application. The contact pathways associated with landscape irrigation are accidental ingestion, inhalation, and touch, while that associated with surface irrigation of wetlands is accidental touch. Therefore, the risk to exposure is higher in case of landscape irrigation as opposed to surface irrigation of constructed wetlands and presently the ISO (2018) standard does not take that into account. Therefore, risk-based targets suited to non-sewered sanitation systems for specific reuse applications should be developed instead of defining targets for loosely defined reuse categories.

Second, ISO (2018) defines targets for both human health protection and environmental protection however, it is unclear whether a fully recycling system must also meet the environmental protection targets. For instance, if reclaimed blackwater is used for toilet flushing, does it need to comply with the environmental performance targets even when there is no discharge of the effluent to the environment? This ambiguity, also highlighted by Reynaert et al. (2020a), could lead to over or under design of the treatment system. Therefore, there is a need for clarity on application of water reuse standards for fully recycling systems.

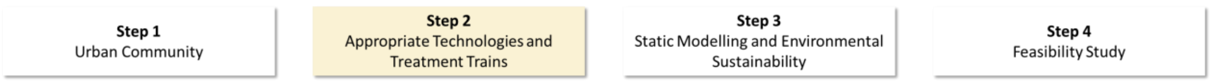
Third, both US EPA (2012) and ISO (2018) do not specify compliance targets for Reuse Category 3 and instead refers to the *National Primary Drinking Water Regulations of the US Environmental Protection Agency* (US EPA, 2024) and the *Guidelines for Drinking Water Quality* (WHO, 2017). These drinking water guidelines were developed for large-scale facilities, where meeting the specified targets and monitoring requirements would be cost-effective. It is unclear how these targets could be achieved in non-sewered systems where access to lab facilities and on-line monitoring may not be possible. Reynaert et al. (2020a) reported that the costs associated with meeting the monitoring requirements specified by US EPA (2012) and ISO (2018) for blackwater reuse in toilet flushing (Reuse Category 2) and hand washing (Reuse Category 3) in South Africa exceeded those predicted for industrial reuse systems. Therefore, there is a need to develop targets and monitoring requirements focused on non-sewered systems especially for Reuse Category 3 applications.

Fourth, the boundary conditions considered in the development of standards differ which could lead to significant differences in system design. For instance, the toilet is considered to be a part of a non-sewered sanitation system by ISO (2018). This means that any nutrient reduction obtained by installing urine separating toilets will also count towards the nutrient reduction targets specified by the standard. This has significant implications for system design as detailed in **4.3.3 Uncertainty analysis**. On the other hand, The *WHO Guidelines for Drinking Water Quality* (WHO, 2017) considers a multi-barrier approach while developing standards. This means that the full sanitation service chain including the toilet, restriction to public, handling of wastewater etc. are considered when developing effluent targets. For example, if WHO (2017) specifies a log reduction value (LRV) of 7 for bacteria for blackwater reuse in production of crops consumed by humans this could be achieved with a combination of technology (3 LRV), on-farm treatment (1 LRV), overnight storage (1 LRV), and boiling in homes (2 LRV). In contrast, the *Guidelines for Water Reuse* (US EPA, 2012) standard follows a single barrier approach. This means that the treatment technology alone should be capable of meeting the LRV of 7 for bacteria. The US EPA approach leads to development of targets that are almost impossible to achieve in developing countries cost-effectively (Schellenberg et al., 2020). Therefore, the boundaries for the applicability of the compliance targets should be clearly defined, and appropriate targets should be selected based on the local context in which the non-sewered sanitation system will be installed.

Thus, three reuse categories and compliance standards applicable to these categories were defined. Although this approach is used further in the thesis because of a lack of alternative approaches, shortcomings were highlighted. Shortcomings include oversimplification of system design, ambiguity in application of targets for fully recycling systems, lack of targets for Reuse Category 3 applications for non-sewered systems, and the lack of coherence between the boundary conditions of different targets.

4.2 Appropriate technologies and treatment trains

Having defined the characteristics of the urban community, the second step was to select appropriate technologies for the given context using pre-selection criteria. Once appropriate technologies are selected, they are configured into treatment trains. Since several treatment trains were capable of achieving the specified effluent targets, decision-making criteria were defined to compare these treatment trains and select one.



4.2.1 Pre-selection

A list of pre-selection criteria was defined in **3.2.1 Pre-selection**, and the reasons for their selection were also highlighted. These criteria are location, scale, nutrient removal, and application. The pre-selection criteria allow for a first shortlist from a long list of possible technologies.

Secondary, tertiary, and advanced treatment technologies were categorized based on three pre-selection criteria (location, scale, nutrient removal) and consolidated into a pre-selection matrix, which can be used to select technologies along the treatment train according to specific contexts by anyone. This is not a comprehensive list of all wastewater technologies but instead a list of most popular/relevant ones derived from the following sources: Coppens (2023), Tare & Bose (2009), Tchobanoglous et al. (2013). This pre-selection matrix is presented in **Table 6**. The process used for developing this pre-selection matrix was detailed in **3.2.1 Pre-selection**.

The pre-selection matrix was used to select technologies for further consideration in this thesis. Technologies listed under the categories 'underground installation', 'strict nutrient removal', and applicable for wastewater treatment at the 'scale of 20-5000 m^3/day' (medium-scale satellite systems) were selected. Certain technologies within these categories, such as Aerobic Granular Sludge, were excluded due to their unsuitability for the low flow rates considered in this thesis (110 m^3/day) (pre-selection criteria: Application, see **3.2.1 Pre-selection**).

- **Underground.** The blackwater reclamation system would be installed underground. This decision was made because: 1) more space is available for an underground system (10,000-15,000 m^2) compared to an above-ground unit (1,500-2,000 m^2), and 2) public resistance to treatment plants is higher for above-ground installations due to the not-in-my-backyard syndrome, leading to significant construction delays (NITI Aayog & Atal Innovation Mission, 2022).

- **Scale 20-5000 m^3/day.** As defined in **4.1.1 Land availability and water quantity**, the urban community considered in this thesis corresponds to a 'small town' or 'medium-scale satellite system' with typical flow rates varying between 20-5000 m^3/day.
- **Strict Nutrient Removal.** The blackwater reclamation system should be capable of complying with strict nutrient removal targets. This decision was made because in the context of an urban community surrounding the NEST in a high-income country like Switzerland, adoption of stricter norms (European Commission, 2022; H. Zhou et al., 2018) necessitates the use of technologies capable of nutrient removal in the present with potential for expansion in the future to meet increasingly stringent targets.

Therefore, based on the above pre-selection process, a list of technologies was selected along the treatment chain. These are listed in **Table 5**. These technologies are configured into treatment trains in the next section. A desk-based review was presented in **2.3 Secondary treatment processes** where the suitability of the secondary treatment technologies listed in **Table 5** for blackwater reclamation was assessed.

Table 5: Pre-selected technologies along the treatment train for blackwater reclamation. Pre-selection criteria adopted were: location, scale, nutrient removal efficiency and application.

Secondary Treatment	Tertiary Treatment	Advanced Treatment
Chemical Precipitation for P removal (ChemP) Activated sludge processes (ASP) Membrane bioreactors (MBR) Moving bed biofilm reactors (MBBR) Packaged plants	UV disinfection (UV) Chlorination (CHLOR)	Microfiltration (MF) Ultrafiltration (UF) Nanofiltration (NF) Reverse osmosis (RO) Depth filtration Surface filtration Adsorption using granular activated carbon (GAC) Gas stripping Ion exchange Electrocoagulation

The following points should be noted about the selected technologies and the pre-selection matrix:

- Packaged plants are often recommended for building-scale wastewater treatment to avoid the costs of civil construction (N. K. Singh & Kazmi, 2018). They are pre-manufactured treatment units, consisting of the same unit processes as traditional plants (e.g., MBBR, ASP, UF), however they are configured efficiently to save space and costs (US EPA, 2000). Some examples of suppliers of packaged plants are Veolia (Veolia Water Technologies, 2024), SSI Aeration (SSI Aeration, 2024), Alfa Laval (Alfa Laval, 2024), B&P Water Technologies (B&P Water Technologies, 2024), Johkasou (Kubota, 2024), and Smith & Loveless Inc. (Smith & Loveless Inc., 2024). The designs for packaged plants should be developed in consultation with the specific manufacturer and they therefore not considered further in this thesis. However, readers are encouraged to consult manufacturers and evaluate the pros and cons of packaged plants compared to civil construction when implementing this methodology in real-life scenarios.
- The pre-selection matrix can be utilized as is or can be modified by other researchers. Additional technologies and pre-selection criteria may be incorporated to tailor the matrix to local contexts. The decisions presented here serve as examples of how to apply this approach, and readers are encouraged to adapt and modify it based on their specific needs.

Table 6: Pre-selection matrix for selecting technologies along the treatment train based on location, scale and nutrient removal targets for the non-sewered sanitation system. TN = Total Nitrogen, TP = Total Phosphorous, NO_3-N = Nitrate-Nitrogen.

<table>
<tr><th>Pre-selection matrix</th><th colspan="2">Small-Scale Onsite
< 20 m^3/day</th><th colspan="2">Medium-Scale Satellite
20 – 5000 m^3/day</th><th>Large-Scale Centralised
> 5000 m^3/day</th></tr>
<tr><td>Secondary Treatment

Above ground + Strict Nutrient Removal

TN > 70% removal
NO_3-N < 10 mg/L
TP > 80% removal</td><td colspan="2">Chemical precipitation for P removal [1]
Packaged plants [2]</td><td colspan="2">Chemical precipitation for P removal [1]
Biological phosphorus removal [1]
Packaged plants [2]
Activated sludge processes [3]
Aerobic granules reactor [4]
Membrane bioreactor
Moving bed biofilm reactor</td><td>Chemical precipitation for P removal [1]
Biological phosphorus removal [1]
Packaged plants [2]
Activated sludge processes [3]
Aerobic granules reactor [4]
Membrane bioreactor
Moving bed biofilm reactor
Trickling filter/activated sludge
Trickling filter/solids contact
Integrated fixed film activated sludge
Upflow anaerobic sludge blanket/Activated sludge</td></tr>
<tr><td>Secondary Treatment

Above ground + Relaxed Nutrient Removal</td><td><15 m^2/m^3
In addition to above:
Trickling filter
Rotating biological contactor
Upflow anaerobic sludge blanket/Trickling filter
Vermifiltration [5]
Anaerobic filter
Anaerobic baffled reactor</td><td>>15 m^2/m^3
In addition to above and left:
Waste stabilisation pond
Duckweed pond system
Lagoons
Constructed wetland
Soil biotechnology [6]</td><td><15 m^2/m^3
In addition to above:
Trickling filter
Rotating biological contactor
Upflow anaerobic sludge blanket/Trickling filter
Vermifiltration [5]
Submerged aerated fixed film reactor</td><td><15 m^2/m^3
In addition to above and left:
Upflow anaerobic sludge blanket reactor/Waste stabilisation pond
Waste stabilisation pond
Duckweed pond system
Lagoons
Constructed wetland
Soil biotechnology [6]</td><td>In addition to above:
Chemical precipitation for P removal [1]
Trickling filter
Membrane biofilm reactors</td></tr>
<tr><td>Secondary Treatment

Underground + Strict nutrient removal

TN > 70% removal
NO_3-N < 10 mg/L
TP > 80% removal</td><td colspan="2">Chemical precipitation for P removal [1]
Packaged plants [2]</td><td colspan="2">Chemical precipitation for P removal [1]
Biological phosphorus removal [1]
Packaged plants [2]
Activated sludge processes [3]
Aerobic granules reactor [4]
Membrane bioreactor
Moving bed biofilm reactor</td><td>Chemical precipitation for P removal [1]
Biological phosphorus removal [1]
Packaged plants [2]
Activated sludge processes [3]
Aerobic granules reactor [4]
Membrane bioreactor
Moving bed biofilm reactor
Trickling filter/activated sludge
Trickling filter/solids contact
Integrated fixed film activated sludge
Upflow anaerobic sludge blanket/Activated sludge</td></tr>
</table>

Secondary Treatment Under ground + Relaxed nutrient removal	In addition to above: Trickling filter Rotating biological contactor Upflow anaerobic sludge blanket/Trickling filter Vermifiltration [5] Anaerobic filter Anaerobic baffled reactor		In addition to above: Trickling filter Rotating biological contactor Upflow anaerobic sludge blanket/Trickling filter Vermifiltration [5] Submerged aerated fixed film reactor		In addition to above: Chemical precipitation for P removal [1] Trickling filter Membrane biofilm reactor	
Tertiary Treatment	UV disinfection Chlorination Above ground: Polishing pond		UV disinfection Chlorination Above ground: Polishing pond		UV disinfection Chlorination Ozonation Pasteurization Advanced oxidation processes	
Advanced Treatment	Microfiltration Ultrafiltration Nanofiltration Reverse osmosis	Depth filtration Surface filtration Adsoprtion Gas stripping	Microfiltration Ultrafiltration Nanofiltration Reverse osmosis	Depth filtration Surface filtration Adsorption Gas stripping Ion exchange Electrocoagulation	Microfiltration Ultrafiltration Nanofiltration Reverse osmosis Photolysis Distillation Electrodialysis	Depth filtration Surface filtration Adsorption Gas stripping Ion exchange Electrocoagulation

[1] Biological phosphorous removal may be considered when P < 0.13 mg/L is required (pre-selection criteria: Application) (Jiang et al., 2005)
[2] Package plants can be considered to avoid civil construction costs for onsite and satellite scale plants (N. K. Singh & Kazmi, 2018)
[3] Activated sludge processes have multiple configurations (Tchobanoglous et al., 2013).
[4] Smallest full scale plant in operation for municipal wastewater treatment is 2000 m^3/day constructed in Netherlands, UK and France (Hamza et al., 2022). Thesis focuses on much lower flows i.e., 110 m^3/day and therefore this technology was not considered further for this thesis (pre-selection criteria: application)
[5] Largest vermifiltration plant in operation in 2024 serves about 300 people (Coppens, 2023)
[6] Lack of full scale case studies.

4.2.2 Configuring treatment trains

The technologies presented in **Table 5** were configured into treatment trains for each reuse category, as shown in **Figure 8**, following the method described in **3.2.2 Configuring treatment trains**. The treatment trains for Reuse Categories 1 and 2 are identical because the log reduction targets for pathogens were the same (**Table 4**).

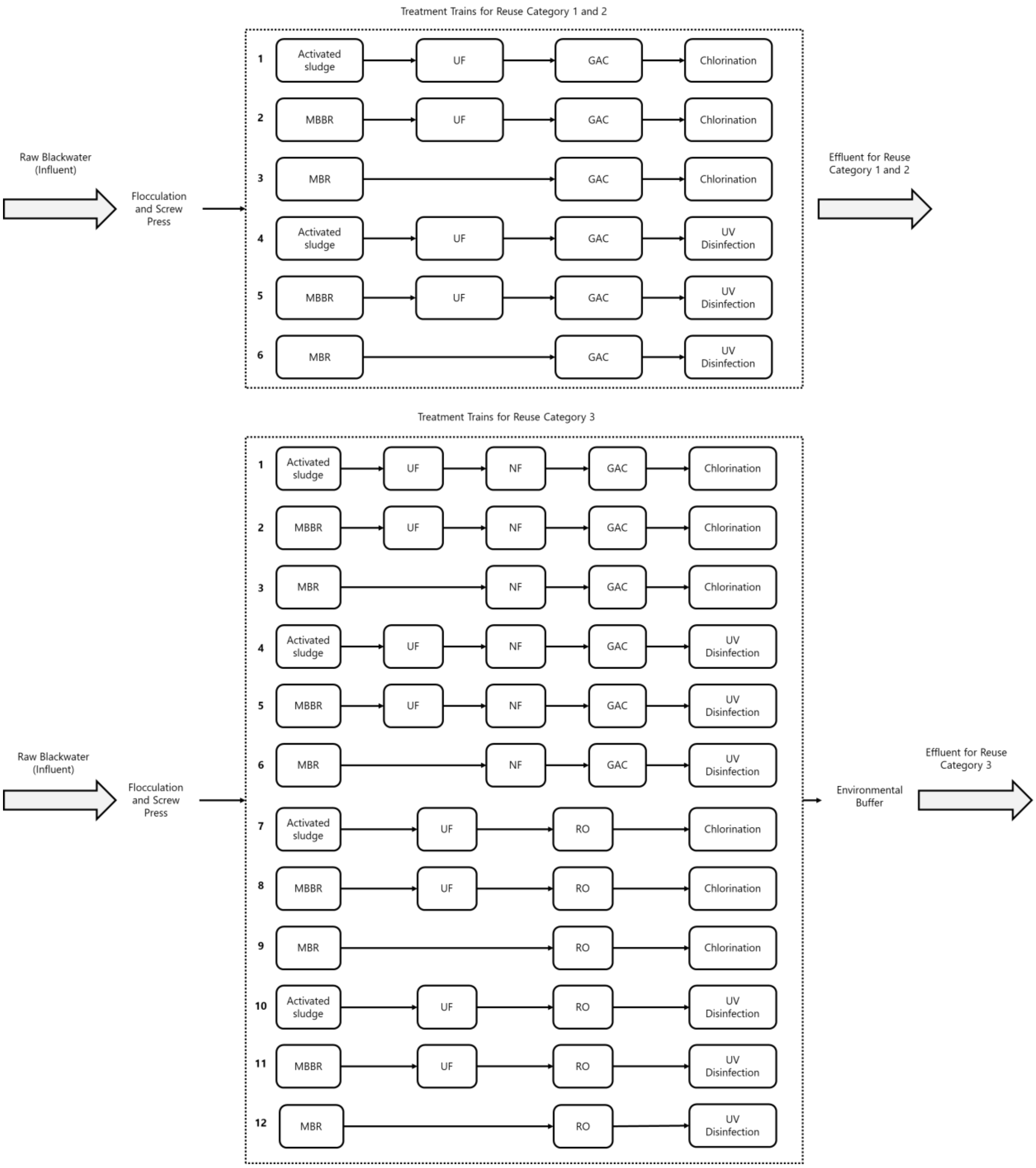


Figure 8: Configured treatment trains for blackwater reclamation in Reuse Category 1, 2, 3 applications consisting of pre-selected technologies. Primary treatment is accomplished using flocculation, settling and a screw press. MBBR =Moving bed biofilm reactor, MBR = Membrane bioreactor, UF = Ultrafiltration, NF = Nanofiltration, RO = Reverse osmosis, GAC = Granular activated carbon filter.

Certain technologies from **Table 5** were not included in the treatment trains because either they could not meet the specified log reduction targets (e.g., surface filtration) or their application was not required (e.g., gas stripping). For phosphorus removal, both electrocoagulation and chemical precipitation can be used. In BioWin, only chemical phosphorus removal can be simulated; therefore, it was selected here. However, considerations for substituting chemical precipitation with electrocoagulation are presented in **4.3.1 Static modelling**.

Hybrid configurations such as an MBBR-MBR were not considered because they are emerging processes with more than 92% of the research performed only in the last decade (Saidulu et al., 2021). Therefore, there is a lack of operational expertise (Pre-selection criteria: Application, see **3.2.1 Pre-selection**).

Therefore, treatment trains for the three reuse categories were configured. For specific reuse applications, additional technologies may be required. For instance, if the blackwater was to be reused in cooling towers (Reuse Category 1), scale formation needs to be controlled (US EPA, 2012). In this case, the generic treatment train developed for Reuse Category 1 or 2 applications as shown in **Figure 8** needs to be adapted to address this specific requirement. Thus, the proposed treatment trains are oversimplified, as was also mentioned in **4.1.3 Reuse possibilities and effluent quality requirements**, and the reader is advised to adapt them when employing this methodology in practice.

4.2.3 Decision-making criteria

The previous step yields several acceptable treatment trains; however, only one treatment train would be implemented in the urban community. Therefore, 14 decision-making criteria were adopted to narrow down to one treatment train per reuse category. These criteria evaluate the economic, environmental, technical, and social sustainability of the treatment train and they are presented in **Table 7**.

The method employed to select and define these decision-making criteria was presented in **3.2.3 Decision-making criteria**. These 14 decision-making criteria differ from the pre-selection criteria as they enable a detailed comparison of treatment trains, whereas pre-selection criteria only allow for elimination of certain technologies.

Table 7: List of decision-making criteria adopted to compare treatment trains for each reuse category along with their definitions. The definitions were derived from Wingelaar (2023). *ML = Million Litres, MLD = Million litres per day.*

Decision-making criteria	Definition
Area occupied (m^2/m^3)	The area of land required for installation of the treatment train.
Capital expenditure ($/MLD)	The total amount of money that is spent on the initial acquisition, construction, and installation of the treatment train.
Operational expenditure ($/MLD)	The total ongoing costs associated with the operation and maintenance of a sanitation unit process or system, such as personnel costs, energy costs, chemical costs, and maintenance and repair costs.
Energy use (kWh/ML)	The total amount of energy required to operate the wastewater treatment system.
Sludge production	The total quantity of sludge produced during the operation of the treatment train.
Impact on people	The potential that the treatment system produces detrimental impact on the staff operating the treatment unit for example due to foul odors, noise, flies, or the release of corrosive and harmful gases such as ammonia, methane.
Impact on surroundings	The potential that the treatment system produces detrimental impact on the surrounding buildings or environment for example due to

	unintended release of corrosive and harmful chemicals to groundwater or surface water.
Operators required	The total number of skilled operators that maybe required to operate the system at a time.
Skills required	The specific set and amount of skills, knowledge, and experience necessary to successfully perform operation and maintenance on the treatment train.
Robustness	The ability of the treatment train to remain operationally effective over its expected lifetime while requiring minimal upkeep, cleaning, or repairments.
Local availability of resources	The treatment unit uses construction and replacement parts that can be acquired locally without requiring imports.
Reliability	The ability of the treatment train to maintain consistence performance despite variations in influent quality or climatic conditions.
Greenhouse gas emissions	The greenhouse gas emissions expected from the treatment train (considered only for secondary treatment technology).
Effluent quality	The quality of effluent produced by the treatment system reliably under varying conditions.

Although the selection and interpretation of these criteria were based on the author's opinions, they are globally relevant. Other readers may follow the method presented in **Figure 5** to select criteria relevant to their specific scenarios, such as comparing the entire sanitation service chain instead of only the sanitation technology.

4.2.4 Selecting one treatment train

The decision-making criteria defined in the previous step were utilized to compare treatment trains and select one for each reuse category. The first four criteria presented in **Table 7** were quantitative indicators, while the remaining were qualitative indicators. Literature sources were used for extracting data on quantitative indicators. On the other hand, personal professional expertise, developed through reviewing key references was used to assign values for qualitative indicators. Complete details about data collection methods were provided in **3.2.4 Selecting one treatment train**.

The absolute values for all indicators were normalized on the scale of 0-1 to facilitate comparison, as illustrated in **Figure 6**. The matrix of normalized scores is presented in **Table 8** for Reuse Categories 1 and 2 and **Table 9** for Reuse Category 3. All treatment trains scored equally on the indicator "Quality", thus the normalized score was set to 0 for this indicator.

The treatment train with the lowest overall score should be selected for implementation in the urban community. However, based on the results in **Table 8** and **Table 9**, several treatment trains produced equivalent scores implying that they were equally suited for the context of the thesis.

The treatment trains with the lowest score for Reuse Category 1 and 2 were:

- MBBR, UF, GAC, and UV disinfection (**Table 8**, number 2)
- MBBR, UF, GAC, and Chlorination (**Table 8**, number 5)

The treatment trains with the lowest score for Reuse Category 3 were:

- MBBR followed by UF, NF, GAC and UV disinfection or chlorination (**Table 9**, number 2 and 5)
- MBR followed by NF, GAC, UV disinfection (**Table 9**, number 6)
- MBBR followed by UF, RO, UV disinfection (**Table 9**, number 11)

Thus, to select one treatment train from the ones presented above, following considerations were made:

(1) Chlorination or UV disinfection were equally suitable. Treatment trains with chlorination were not considered further because UV scored better on the criteria 'impact on people and surrounding'.
- Wingelaar (2023) showed that the criteria 'impact on people and surrounding' was the most important criteria for sanitation system design for both users and experts in the Hagonoy municipality in the Philippines. In Lishu County, China, construction cost (defined as capital expenditure in this thesis) was the most important design criteria for a decentralized treatment plant (Liu et al., 2020). Chlorination and UV rank equally on this criteria and were therefore equally suitable. In Varanasi, India where operational expenditures was the most important, UV disinfection would be a more suitable option (Srivastava & Singh, 2022).
- Based on the above discussion, we see that selection of an appropriate option is governed by the 'weight' that is assigned to a decision-making criteria. In this thesis, it was assumed that the criteria 'impact on people and surroundings' is the most important as negative impacts can often lead to misgivings about non-sewered sanitation. Therefore, treatment trains with UV disinfection were considered further.
- In addition, the need to store, transport and handle hazardous chemicals, and additional costs associated with dechlorination (if required) are also reduced with UV disinfection (US EPA, 2003). However, a significant disadvantage of UV disinfection is the lack of residual disinfection capacity. UV disinfection could be used in applications where the blackwater is reused immediately and on-site (for e.g., vehicle washing) instead of applications that require long transport in sewer pipes (for e.g., fire-fighting). Treatment trains for applications requiring discharge to the environment (for e.g., silviculture) can also include UV to avoid dechlorination costs (US EPA, 2003).

(2) Both MBBR and MBR were found to be equally suitable for Reuse Category 3. However, only the MBBR-based treatment train produced the lowest score for Reuse Categories 1 and 2. Therefore, MBBR was selected for further consideration, as it generally requires fewer operational considerations compared to an MBR (Tare & Bose, 2009). An MBR could be chosen in areas where operational costs can be managed by the service provider rather than the user (Wingelaar, 2023). This makes it easier to manage the system throughout its lifecycle. For example, an MBR could be considered for business establishments such as restaurants, whereas an MBBR could be selected for building-scale treatment.

(3) NF + GAC and RO score equally well for Reuse Category 3. NF + GAC were selected in this thesis due to their better scores on the category 'operational expenditure' and 'energy requirements'.
- NF + GAC requires less energy when compared to RO, making the combination more energy-efficient. In addition, operational expenditures associated with RO are higher compared to NF + GAC. Further, NF membranes are less prone to fouling, and allow selective removal of ions, facilitating the retention of essential minerals such as sodium and potassium while maintaining water quality for reuse applications (Tchobanoglous et al., 2013).
- In addition, NF membranes allow for higher recovery rates when compared to RO which is essential for reuse applications. RO membranes can be considered when influent blackwater has high concentrations of monovalent chlorine ions (from toilet cleaners, bleaches) that will not be removed in NF.

Table 8: Normalised scores of decision-making criteria for the six treatment trains designed for Reuse Category 1 and 2. 1 = ASP + UF + GAC + Chlorination, 2 = MBBR + UF + GAC +Chlorination, 3 = MBR + GAC + Chlorination, 4 = ASP + UF + GAC + UV disinfection, 5 = MBBR + UF + GAC + UV disinfection, 6 = MBR + GAC + UV disinfection. ASP = Activated sludge processes, UF = Ultrafiltration, GAC = Granular activated carbon filter.

Decision-Making Criteria	**1**	**2**	**3**	**4**	**5**	**6**
Area occupied	1	0,4	0	1	0,4	1
Capital expenditure	0,4	0	1	0,4	0	1
Operational expenditure	1	0,88	0,75	0,25	0,13	0
Energy use	0,19	0	0,68	0,5	0,32	1
Sludge production	1	0,5	0	1	0,5	0
Impact on people	0,5	1	0,5	0	0,5	0
Impact on surroundings	1	1	1	0	0	0
Operators required	0,5	0	0	1	0,5	0,5
Skills required	0	0,33	0,67	0,33	0,67	1
Robustness	0,33	0	0,67	0,67	0,33	1
Local availability of resources	0	0,33	0,67	0,33	0,67	1
Reliability	1	1	0	1	1	0
GHG emissions	1	0	1	1	0	1
Effluent quality	0	0	0	0	0	0
SUM	**8**	**5**	**7**	**7**	**5**	**7**

Table 9: Normalised scores of decision making criteria for the six treatment trains designed for Reuse Category 3. 1 = ASP + UF + NF + GAC + Chlorination, 2 = MBBR + UF + NF + GAC + Chlorination, 3 = MBR + NF + GAC + Chlorination, 4 = ASP + UF + NF + GAC + UV disinfection, 5 = MBBR + UF + NF + GAC + UV disinfection, 6 = MBR + NF + GAC + UV disinfection, 7 = ASP + UF + RO + Chlorination, 8 = MBBR + UF + RO + Chlorination, 9 = MBR + RO + Chlorination, 10 = ASP + UF + RO + UV disinfection, 11 = MBBR + UF + RO + UV disinfection, 12 = MBR + RO + UV disinfection. ASP = Activated sludge processes, UF = Ultrafiltration, NF = Nanofiltration, RO = Reverse Osmosis, GAC = Granular activated carbon filter.

Decision-Making Criteria	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Area occupied	1	0,64	0,4	1	0,64	0,4	0,6	0,24	0	0,6	0,24	0,2
Capital expenditure	0,06	0	0,16	0,06	0	0,16	0,09	0,03	0,19	0,09	0,03	1
Operational expenditure	0,79	0,69	0,59	0,2	0,1	0	1	0,9	0,8	0,41	0,31	1
Energy use	0,05	0	0,18	0,13	0,08	0,26	0,4	0,35	0,53	0,48	0,43	1

Sludge production	1	0,5	0	1	0,5	0	1	0,5	0	1	0,5	0
Impact on people	0,5	1	0,5	0	0,5	0	0,5	1	0,5	0	0,5	0
Impact on surroundings	1	1	1	0	0	0	1	1	1	0	0	0
Operators required	0,5	0	0	1	0,5	0,5	0,5	0	0	1	0,5	0,5
Skills required	0	0,33	0,67	0,33	0,67	1	0	0,33	0,67	0,33	0,67	1
Robustness	0,33	0	0,67	0,67	0,33	1	0,33	0	0,67	0,67	0,33	1
Local availability of resources	0	0,33	0,67	0,33	0,67	1	0	0,33	0,67	0,33	0,67	1
Reliability	1	1	0	1	1	0	1	1	0	1	1	0
GHG emissions	1	0	1	1	0	1	1	0	1	1	0	1
Effluent quality	0	0	0	0	0	0	0	0	0	0	0	0
SUM	**7**	**5**	**6**	**7**	**5**	**5**	**7**	**6**	**6**	**7**	**5**	**8**

In conclusion, the results from the decision matrix complemented with practical insights suggest that treatment trains with MBBR outperform others for the hypothetical scenario of the urban residential community considered in this thesis. The treatment train comprising MBBR, UF, GAC, and UV Disinfection, which was selected for blackwater reclamation in Reuse Categories 1 and 2 applications. For Reuse Category 3 applications, the treatment train consisting of MBBR, UF, NF, GAC, and UV disinfection was selected. As mentioned previously, chemical precipitation was included in the above treatment chain for phosphorous removal in BioWin modelling and considerations for replacing it with electrocoagulation are presented in **4.3.1 Static modelling**.

Readers can create similar decision matrices to gain insights into the relative advantages and disadvantages of different technologies. By supplementing these matrices with engineering and scientific knowledge, they can effectively select suitable treatment trains for diverse contexts. It is essential to complete the results from the decision-matrix with engineering insights to arrive at one optimal solution. Readers looking to apply this method in practice should consider the following points:

- A disadvantage of the approach developed in this thesis is that the values assigned for qualitative indicators (or decision-making criteria) were based on author's expertise and not verified using other means such as discussion with experts, due to lack of resources and time. In spite of outreach efforts via Reddit, LinkedIn, Emails and WhatsApp, it was difficult to connect with operators who had experience with maintaining non-sewered treatment plants and could cross-verify the values assigned to different treatment trains. Other researchers referring to this thesis can employ other/better data collection methods (e.g., interviews with users and experts) to assign values for qualitative indicators for a specific context and urban community following the method described by Wingelaar (2023).

- In this thesis, all decision-making criteria were weighted equally, which may not be suitable for every urban community. For example, in low-income countries, electricity supply is often the most critical factor for treatment plant operation, whereas in high-income countries, resource recovery is typically more important for non-sewered sanitation (WaterAid, 2019). Equal weighting of decision-making criteria can overlook these differences, potentially leading to suboptimal solutions. Therefore, readers should first clearly define the goals that the non-sewered sanitation system must achieve. The criteria should then be weighted, modified, or supplemented as needed to ensure an accurate comparison of treatment options. Therefore, this is a strength of this approach that it has a possibility for contextualization by adapting the weights.

4.3 Static modelling and environmental sustainability

After selecting one treatment train for each reuse category from the previous step, the next step was to perform unit sizing and conduct an uncertainty analysis. The results from these analyses were used to select one reuse category (from the three defined in Step 1) for future implementation in the urban community. Additionally, the environmental sustainability of a complete non-sewered sanitation system using a carbon footprint analysis was evaluated to generate insights on benefits and trade-offs of a non-sewered sanitation approach.

4.3.1 Static modelling

Unit sizing calculations for the treatment train selected in the previous step were performed using methods described in **3.3.1 Static modelling**. The results from these calculations and BioWin modelling are presented in **Figure 9** for the non-potable reuse treatment train (Reuse Category 1 and 2) and in **Figure 10** for the potable reuse treatment train (Reuse Category 3).

The volume of the reactors, the media fill percent for the MBBR, and the recycle ratios were determined iteratively. Several assumptions govern the design calculations. These assumptions and formulae used to calculate unit sizes are presented in **Appendix 6**. A brief description of an MBBR was presented in **2.3 Secondary treatment processes**.

The following paragraphs provide detailed discussions on the process designs.

4.3.1.1 Reuse category 1 and 2 (Non-potable reuse)

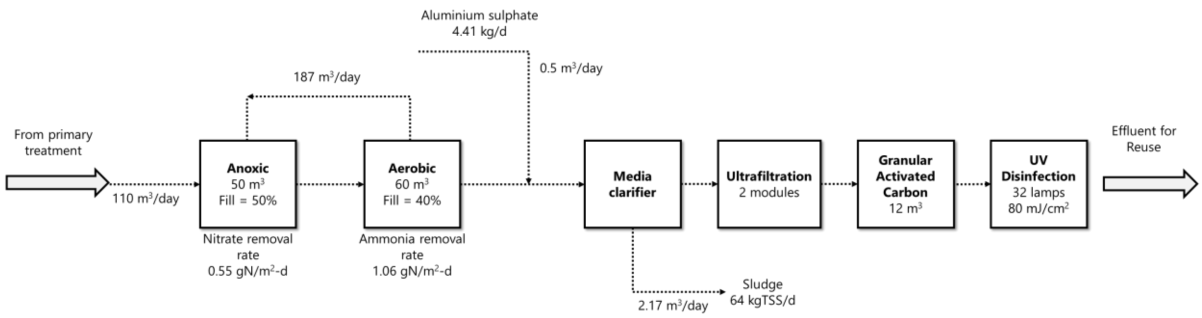


Figure 9: Treatment train for Reuse Category 1 and 2. See also Appendix 6 for assumptions and formulae that govern unit sizing.

The treatment train for Reuse Categories 1 and 2 consists of an MBBR, chemical precipitation for phosphorous removal, UF, GAC, and UV. The MBBR consists of an anoxic and aerobic tank with internal recycle, and is responsible for removing particulate and soluble biodegradable organics, and nutrients (e.g., nitrogen and phosphorous). The UF removes particulate matter and pathogens, the GAC removes soluble non-biodegradable compounds, and the UV disinfection step eliminates the remainder of the pathogens (Tchobanoglous et al., 2013).

The anoxic and aerobic tanks of the MBBR contain plastic carrier media kept in suspension by aeration devices, facilitating the growth of attached biomass. Denitrification occurs in the anoxic tank, while the aerobic zone is responsible for COD removal, ammonification, and nitrification. Nutrients are partially removed through biomass uptake for growth. However, most nitrogen removal is achieved through nitrification and denitrification, while phosphorus removal is primarily accomplished through chemical precipitation (Tchobanoglous et al., 2013). The suspended biomass that sloughs off from the carrier media is carried from one tank to another with the wastewater flow, while the biomass growing on the carrier media remains in the specific anoxic or aerobic tank (EnviroSim Associates Limited, 2024). The carrier media also stay in the particular tank and are not transferred from one to another. The suspended biomass is removed in the media clarifier. Before reaching the clarifier, aluminum sulfate is dosed for phosphorus removal through chemical precipitation. Although chemical dosing for phosphorus removal can be accomplished before or after the MBBR, optimal removal occurs after the MBBR. This is because polyphosphorus and organic phosphorus in the influent, which are harder to remove, are converted to orthophosphorus by heterotrophic bacteria in the aerobic tank (secondary treatment), making them easier to precipitate downstream of the MBBR. Additionally, chemical dosing after the MBBR avoids phosphorus-limiting conditions within the MBBR, where phosphorous is one of the nutrients required by the biomass for growth. The metal salt aluminium sulfate was selected due to its wide availability and low cost, though other chemicals such as ferric chloride or polyaluminum chloride could also be used depending on local availability (Tchobanoglous et al., 2013).

In this thesis, a media clarifier was considered for biomass and solids separation after the MBBR instead of traditional gravity sedimentation/clarification, and flotation commonly used in activated sludge plants. The media clarifier is recommended because biomass separation in MBBR systems is more challenging compared to activated sludge systems (Nof et al., 2024). Sludge from MBBR contains only excess biomass since there is no sludge recycling, resulting in effluent TSS concentration of 100-250 mg/L (as opposed to 2500-3000 mg TSS/L in activated sludge plants) (Tchobanoglous et al., 2013). Therefore, the particle size distributions in MBBR systems can be highly variable with more small size fractions. Particle separation using traditional gravity sedimentation/clarification and flotation after MBBR systems is not favorable; and a media clarifier is therefore recommended (Nof et al., 2024). The media clarifier is a compact secondary biomass separation unit dealing with the typical sedimentation challenges of pure MBBR systems, by the integration of clarifier and a plastic media layer (Nof et al., 2024). The media clarifier requires small footprint, relative to conventional clarifiers, and is simple to operate. In addition, it eliminates scum problems and reduces energy consumption (Nof et al., 2024).

The complete treatment train occupies an area between 80-100 m^2 and consumes electrical energy ranging from 0.8 to 2 kWh/m^3 based on the BioWin model. For phosphorus removal, 4.4 kg/day of aluminum sulfate was required.

The average power requirement for the transport and treatment of wastewater in sewered sanitation systems ranges from 1 to 10 kWh/m^3 (Olsson, 2012), so the proposed system uses about half the energy of a centralized plant. However, if all energy-consuming units would be added up such as instrumentation devices and pumps, the treatment train would possibly consume the same amount of energy (or higher) as a sewered system.

In contrast, previously reported power consumption in non-sewered blackwater reclamation systems varies widely depending on the technology used. For example, Reynaert et al. (2020a) report that a blackwater recycling unit comprising an MBR, GAC, and an electrolysis flow cell consumed 0.4-6.9 kWh/m^3. Another example by Rogers et al. (2018) shows a blackwater recycling unit with GAC and an electrochemical unit consuming 4-19 kWh/m^3 of electrical energy. Thus, in terms of power consumption, the treatment train considered in this thesis performs better than other non-sewered treatment trains.

The proposed treatment train occupies a space of 0.8-1 m^2/m^3. Compared to other full-scale decentralized treatment plants, such as those using MBR (0.3-0.8 m^2/m^3), MBBR (0.8-1 m^2/m^3), and packaged plants (0.125-0.8 m^2/m^3) (N. K. Singh et al., 2015; N. K. Singh & Kazmi, 2018), the proposed system requires more space than an MBR. The lower area requirement of an MBR is because the micro- and ultrafiltration membranes are integrated into the secondary treatment tanks. Packaged plants also occupy less space, which supports the discussion that they may be preferred for single-building scale treatment to save space and civil construction costs as mentioned in **4.2.1 Pre-selection**. However, the available space in the urban community considered here was approximately 10-15 m^2/m^3 (**4.1.1 Land availability and water quantity**), so the proposed system occupies significantly less space than what is available.

4.3.1.2 Reuse category 3 (Potable reuse)

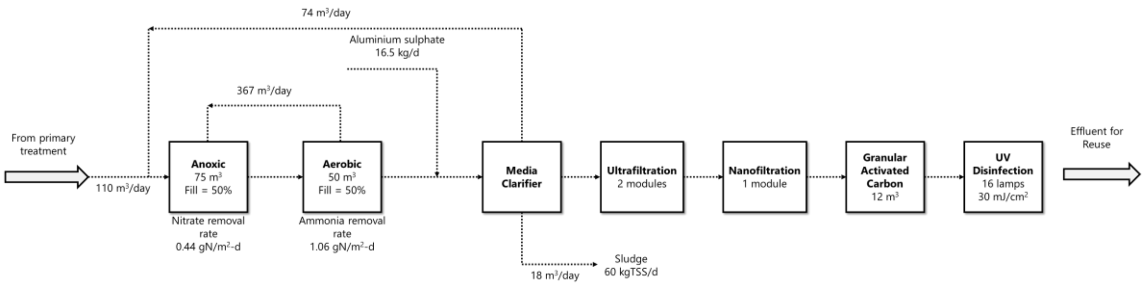


Figure 10: Treatment train for Reuse Category 3. See also Appendix 6 for assumptions and formulae that govern unit sizing.

The treatment train for Reuse Category 3 consists of an MBBR, chemical precipitation for phosphorous removal, UF, NF, GAC, and UV. The MBBR, which includes an anoxic and aerobic tank with internal recycle, is responsible for removing particulate and soluble biodegradable organics and nutrients (e.g., nitrogen and phosphorous). The UF removes particulate matter and pathogens, the NF further removes pathogens and multivalent ions, GAC removes soluble non-biodegradable compounds, and the UV disinfection step eliminates the remainder of the pathogens.

The complete treatment train occupies an area between 80-100 m^2 and consumes electrical energy ranging from 3 to 5 kWh/m^3 based on the BioWin model. The energy consumption is higher due to the nanofiltration membrane. For phosphorus removal, 16.5 kg/day of aluminum sulfate would be required which is four times more than that required for non-potable applications.

In addition to the considerations presented earlier, the process configuration designed here includes a sludge recycle line from the media clarifier to the anoxic tank. This configuration is called an Integrated Fixed Film Activated Sludge (IFAS) design. IFAS is a modification of the MBBR. The return sludge line enhances nitrogen removal without requiring external carbon addition, helping meet the stricter compliance targets for Reuse Category 3 (NO_3-N < 10 mg/L, **Table 4**). The return sludge line increases the concentration of suspended biomass in the system. Although at low temperatures (<20°C; design temperature = 15°C), the attached biomass contributes significantly to nitrogen removal, the suspended biomass also plays a crucial role due to the 'seeding effect' from the biofilm (di Biase et al., 2019). It is because of this additional suspended biomass that the stricter effluent targets set for Reuse Category 3 applications (NO_3-N < 10 mg/L, NO_2-N < 1 mg/L) could be met without the requirement of external carbon source for denitrification. Thus, while the MBBR was initially deemed the optimal choice based on pre-selection and decision-making matrix (**4.2.4 Selecting one treatment train**), BioWin modelling revealed that the IFAS configuration outperformed the MBBR in meeting the effluent targets set for Reuse Category 3.

4.3.1.3 Considerations

Several considerations with respect to the static designs presented in previous sections were identified and they are listed below for the benefit of the reader looking to apply these methods and results in practice.

- **Performance parameters.** The space and energy requirements calculated in the above steps provide a very general estimate and should not be extrapolated for other systems. In real-life scenarios, these metrics will vary significantly as the designs were produced based on various assumptions. For example, the DO level was assumed to be constant at 5 mg/L for the aerobic zone. This largely governs the energy requirement, with a lower or higher DO concentration, the energy requirement will vary significantly. Therefore, the values presented here serve only as an indicator to demonstrate the increased demands of practicing potable reuse over non-potable reuse. The same applies to the calculations for chemical consumed and sludge production.
- **Return sludge line.** Although the IFAS configuration was considered here for potable reuse applications as it improved the biomass concentration and led to elimination of the requirement of external carbon dosage, maintaining the required mixed liquor suspended solids concentration is often a challenge (Brault et al., 2022a). Additionally, the pumping requirement is increased with the IFAS design due to the return sludge line. Therefore, in real-life situations, the pros and cons of introducing a return sludge line should be carefully assessed.
- **Sludge management.** Proper disposal of sludge is essential. When dealing with sludge generated from an MBBR treatment system in an urban area, several options for sludge management and disposal are available. These include dewatering through mechanical processes like centrifuges, belt filter presses, or screw presses, composting, anaerobic digestion, transport to facilities for land application, incineration, or sludge drying using beds (Strande et al., 2014; Tchobanoglous et al., 2013). The choice of sludge management strategy should consider local regulations, environmental impact, costs, available infrastructure, and community acceptance (Leyva-Díaz et al., 2020).
- **Peripheral units.** Several peripheral items are needed for the accurate functioning of the treatment plant, such as pumps, aeration devices, instrumentation, media retention screens, chemicals for cleaning membranes, spare parts, and granular activated carbon regeneration or disposal facilities. Although not considered here, these units are a significant part of a treatment plant, and the reader should compile a bill of materials, including all peripheral units, for estimation of costs, energy requirements, and space requirements.
- **Plastic pollution.** Attached growth treatment processes like MBBR utilize plastic media, raising concerns about plastic pollution due to media fragmentation and loss. This can result in microplastic pollution, affecting the environment and potentially human health (Ariyanti & Widiasa, 2023). To mitigate this risk, it is crucial to use high-quality, durable media, ensure proper containment, and conduct regular monitoring and maintenance (Levapor Biofilm Technologie, 2024). Exploring alternative materials (e.g., foam, green-bed media), and developing replacement protocols can also help minimize the risk of plastic pollution (Ariyanti & Widiasa, 2023; Levapor Biofilm Technologie, 2024).
- **Alternatives to chemical dosing.** Phosphorus removal was achieved through chemical precipitation using aluminum sulfate. However, the procurement, storage, and dosing of chemicals adds to the plant's operational burden. Therefore, alternatives such as electrocoagulation may be considered. This process relies on the in-situ generation of coagulant species, eliminating the need for external chemicals (Zheng et al., 2022). Previous studies have shown the potential of this technology for phosphorus removal, but it comes with higher electricity consumption (D. D. Nguyen et al., 2016). Therefore, while the trade-offs need to be carefully evaluated, electrocoagulation is proposed as an alternative to chemical dosing. However, since electrocoagulation is an electro-

chemical technology, scaling it down may not be cost-effective (Brault et al., 2022a). Therefore, careful consideration is needed before replacing chemical precipitation with electrocoagulation.

Thus, unit sizing calculations were performed for the selected treatment train for non-potable and potable reuse applications. The design outputs were compared to sewered and non-sewered designs from literature, and considerations were provided for adapting the results in practice.

4.3.2 Selecting one reuse category

After designing the treatment trains for each reuse category, the next step was to determine which reuse category would be most suitable for on-ground implementation in the urban community. To this end, interviews with experts from CDD, India, and Eawag were conducted as detailed in **3.3.2 Selecting one reuse category**. Please note that the reuse category most suitable for pilot testing in the NEST is defined in **4.4.1 Considerations for implementation in NEST**.

- Giuseppe Congiu, a project engineer with an environmental engineering background, has experience with operating a greywater treatment system in the NEST. The system is a pilot scale unit consisting of a hybrid MBBR-MBR, biological activated carbon, and chlorination. A nanofiltration unit is also being tested as a part of the same setup. According to him, a suitable reuse category should be defined based on 'ease of operation'. Considering the difficulties he has faced with operating the nanofiltration unit and a lack of operational expertise even at Eawag, he believed that for a building scale system, nanofiltration or reverse osmosis would be too complex. In addition, he also mentioned that water loss in the nanofiltration unit at Eawag was 30% and believed that high water losses are not justified for reuse-focused systems. He therefore suggests the urban community to implement treatment trains for Reuse Category 1 or 2.
- David Hasler, a mechanical engineer, has experience with designing prototypes and pilot scale treatment systems. According to him, a suitable reuse possibility should be defined based on 'demand for the recycled water'. Considering public resistance to potable reuse applications and a higher demand for recycled water in non-potable applications, he selected Reuse Category 2 as the most suitable for implementing in the urban community.
- Rohini Pradeep, is a project manager at CDD Society in India. She has 15-year experience in design and implementation of decentralised wastewater treatment. Rohini considers that 'operational expertise and expenditure' should be the deciding criteria. Considering that the operation of a non-sewered sanitation system is often handled by the residents of the community, it is imperative that operational expenditures are at a minimum and the system can function without minimal upkeep. Therefore, she suggests the residents of the urban community to test non-potable treatment trains (Reuse Category 1 or 2).
- Eberhard Morgenroth agreed with the David's comments that the suitable reuse possibility would be one where demand for the recycled water is the highest.
- Michael Vogel agreed with the Guiseppe's comments that the suitable reuse possibility would be one which is easiest to operate.

The informal interviews yielded varying insights on 'how' a suitable reuse category should be defined. However, the interviewees concurred that the treatment train designed for Reuse Category 2 would be ideal for on-ground implementation in the hypothetical urban community considered in this thesis.

4.3.3 Uncertainty analysis

Having selected the treatment train for Reuse Category 2 as the most suitable for pilot-testing in the urban community, the next step was to quantify the effect of variability in design input on design output through an uncertainty analysis (Geffray et al., 2019), considering that the designs produced in **4.3.1**

Static modelling were based on multiple assumptions. The different scenarios tested as part of the uncertainty analysis were described in detail in **3.3.3 Uncertainty analysis**. A brief description of each scenario is presented below for reader's reference.

- **Co-treatment of greywater and blackwater.** Initial designs assumed separate collection of blackwater and greywater. For existing urban areas without segregation but desiring reuse, the impact of co-treating greywater and blackwater is assessed.
- **Degree of urine separation.** Some toilets divert urine, while others do not. Higher urine diversion could enhance nutrient removal, given urine contains 70% of nitrogen and 50% of phosphorus in wastewater. The effects of no separation and complete separation of urine are evaluated.
- **Blackwater supernatant treatment.** Previous designs treated the screw press water quality. However, screw press liquid may be inferior due to floc breakup from shear forces. The benefits of treating blackwater supernatant instead are evaluated.
- **Worst efficiency of the screw press.** Designs used flow-weighted average concentrations. These can vary due to primary treatment efficiency fluctuations. The impact of worst-case efficiency of primary treatment on downstream system design was evaluated.
- **Low and high flow conditions.** Designs were based on average flow conditions from the NEST building. Unit sizing under peak and low flow conditions was assessed.
- **Flow conditions in other communities.** The flow rates were scaled up from those reported for NEST. NEST data may not represent typical urban communities due to its unique urban environment. Average minimum and maximum flow rates from literature sources for other urban communities were tested.

Table 10 shows the variability in the input parameters relative to the baseline scenario, while **Table 11** illustrates the variability in output (results) relative to the baseline scenario. For an explanation of how the input parameters were derived for each scenario and a schematic representation of the different scenarios of the uncertainty analysis, please refer to **Appendix 8**. Please note unit sizes were calculated only for the secondary treatment unit for the uncertainty analysis.

Table 10: Description of scenario evaluated for uncertainty analysis with indication for variation in design input.

Scenario evaluated	**Input to secondary treatment**				
	Flow rate	**TSS**	**COD**	**TN**	**TP**
	m^3/day	**mg/L**	**mg/L**	**mg/L**	**mg/L**
Baseline scenario (section 4.3.1)	110	500	1164	160	21
Co-treatment of greywater and blackwater	500	48	145	50	5.2
No urine separation (All urine)	110	148	336	211	18
100% urine separation (No urine)	110	220	660	25	7
Blackwater supernatant treatment	110	320	853	149	19
Worst efficiency of screw press	110	500	1316	168	20
NEST community lowest flow	6	500	1164	160	21
NEST community highest flow	600	500	1164	160	21
Other urban communities: Low flow conditions	50	500	1164	160	21
Other urban communities: High flow conditions	150	500	1164	160	21

Table 11: Variability in design output recorded for different scenarios evaluated as a part of the uncertainty analysis.

Scenario evaluated	Flow rate	Area	External Carbon	Aluminium Sulphate	Sludge production	Power	MBBR or IFAS
	m^3/day	m^2	gCOD/L	kg/day	kg TSS/day	kW	-
Baseline scenario (section 4.3.1)	110	45	0	4	64	5	MBBR
Co-treatment of greywater and blackwater	500	80	70	22	46	9	IFAS
No urine separation (All urine)	110	64	95	14	35	8	IFAS
100% urine separation (No urine)	110	16	0	0	35	2	MBBR
Blackwater supernatant treatment	110	44	0	4	35	5	MBBR
Worst efficiency of screw press	110	48	0	2	69	5	MBBR
NEST lowest flow	6	9	0,0	0,4	3,4	0,4	MBBR
NEST highest flow	600	300	0	22	369	24	MBBR
Other urban communities: Low flow conditions	50	22	0	2	30	2	MBBR
Other urban communities: High flow conditions	150	45	0	4	94	5	MBBR

Subsequent sections provide discussions for each case. Please note all recommendations give below are for the hypothetical urban community. Recommendations for NEST are provided in section xxx.

4.3.3.1 Co-treatment of greywater and blackwater

The static design for the scenario co-treatment of greywater and blackwater is illustrated in **Figure 11**. This scenario has increased requirement over almost all the parameters summarized in **Table 11**. The increased chemical demand is because the system treats the complete urine fraction whereas in the baseline scenario, some urine was separately collected. The area and power requirements are higher because of the increased flow rate, COD and nutrient loading. The sludge production is lower when compared to the base case which could be because of the lower loading of suspended solids due to the dilution from greywater. It could also be because of BioWin's assumptions. BioWin calculates the TSS in influent based on the specified influent inert suspended solids concentrations. Since the influent inert suspended solids concentration was not measured during the thesis, the inert solids concentrations was adjusted until the simulated TSS in BioWin matched the measured value. This could introduce a discrepancy in the results.

In spite of the added complexity due to the return sludge line and external carbon requirement for denitrification, a combined treatment system can be ideal in urban areas due to the risk of misconnections in source separating systems. Tolksdorf & Cornel (2017) show that in China misconnections rates as low as 6-8% between greywater and blackwater piping meant that the non-sewered system treating greywater needed to be upgraded from a simple COD removal system to a nutrient removing system. Therefore, co-treatment can be recommended in densely packed urban areas.

The external carbon requirements for the combined system could be fulfilled using chemicals such as methanol or to avoid supply chain issues associated with procurement of chemicals, using local sources such as woodchips, corncobs, toilet paper, or effluent from industries (Fu et al., 2022; Oakley et al., 2010; Z. Xu et al., 2009). Instead of using aluminium sulphate for phosphorous precipitation, adsorption, enhanced biological phosphorous removal, ion exchange or electrocoagulation can be used (Bunce et al., 2018; D. Nguyen et al., 2016). Thus, co-treatment can be simplified by exploring alternatives to chemical dosage for nutrient removal.

A direct comparison to only blackwater treatment unit considered in the baseline scenario cannot be drawn, as the baseline scenario must also includes a separate greywater and urine treatment system that were not considered in this case. Therefore, while separate collection and treatment of greywater and blackwater may simplify the treatment of individual streams, the risk of misconnections in urban areas suggests that co-treatment could be beneficial to mitigate these risks and enable reuse in newly developing urban communities. The pros and cons of each approach should be carefully evaluated for the specific urban context.

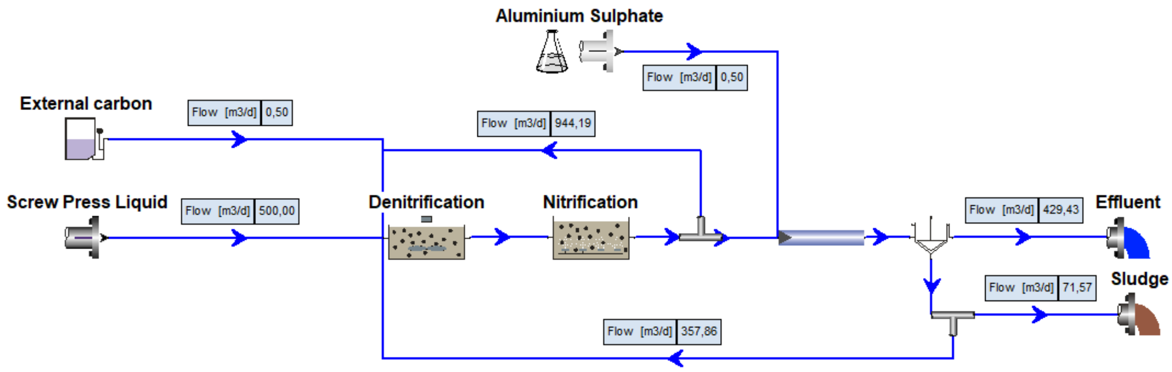


Figure 11: Biowin model for uncertainty analysis scenario: Co-treatment of greywater and blackwater.

4.3.3.2 Urine separation

With 100% urine separation, the need for nitrification, denitrification, and chemical precipitation for phosphorous removal diminishes, as effluent compliance targets can be met through urine-separating toilets and a hypothetical urine treatment unit. This unit, assumed to safely collect and treat urine before discharge or reuse, resembles systems described in existing literature and similar to those in the NEST (Faust et al., 2022). While achieving 100% urine separation through urine separating toilets could be impractical due to technological limitations, the results from the design model serve as a reference to illustrate the impact of improved urine separation on blackwater treatment. The BioWin model for this scenario is detailed in Figure 12. Although, enhanced urine separation simplifies blackwater treatment, it also introduces additional complexity because a separate urine treatment system will now be required. This complexity leads to an increased carbon footprint, as discussed in **4.3.4 Carbon footprint analysis**. However, with 100% urine separation, simpler technologies can be used (e.g., vermifiltration) for blackwater reuse since only COD removal is required which could also affect the overall carbon footprint of the non-sewered system. On the other hand, with 0% urine separation, the total nutrient loading to the system increases which increases the chemical demand and the power requirement. The BioWin model for this scenario is presented in Figure 13.

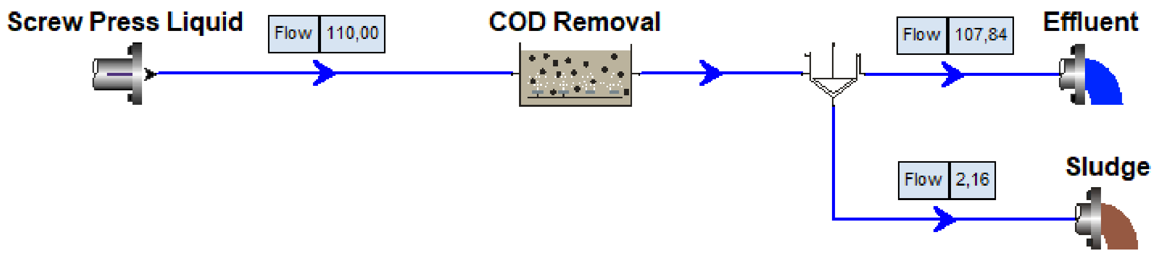


Figure 12: Biowin model for uncertainty analysis scenario: 100% urine separation.

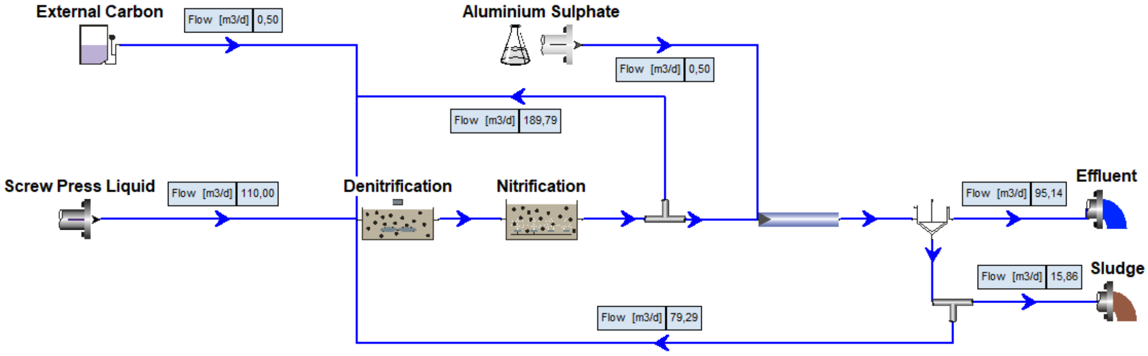


Figure 13: Biowin model for uncertainty analysis scenario: 0% urine separation.

From a life cycle perspective, researchers are divided on the degree of source separation that is most sustainable. For instance, Xue et al. (2016) showed with LCA that urine recovery systems, household-installed composting toilets, blackwater treatment for energy recovery, and greywater treatment for reuse back to toilets, deployed at a community scale were better than centralized systems at a city scale in terms of eutrophication, global warming, and energy potentials. On the other hand, Oarga-Mulec et al. (2023) showed that blackwater composting with energy recovery was the most environmentally sustainable option (based on aggregate score for eight LCA indicators) when compared with decentralised source separating system or a combined blackwater and greywater treatment unit. Based on the boundary conditions considered, and the context and the methods used to perform a life cycle study, any alternative could be equally promising. Therefore, urine separation and treatment requires a holistic assessment beyond technical comparisons alone before implementation.

4.3.3.3 Supernatant treatment and worst efficiency of primary treatment

Compared to the baseline scenario, treating either the blackwater supernatant or at the screw press liquid at the worst efficiency of primary treatment does not seem to affect performance. The BioWin models are depicted in **Figure 14** and **Figure 15**. While a slightly larger area is needed for biomass growth in the MBBR compared to the baseline scenario at the worst efficiency of primary treatment, it remains within an acceptable range, demonstrating the attached growth's resilience in handling variations in blackwater composition. Thus, even under varying primary treatment conditions, downstream treatment with an MBBR remains largely unaffected (**Table 11**).

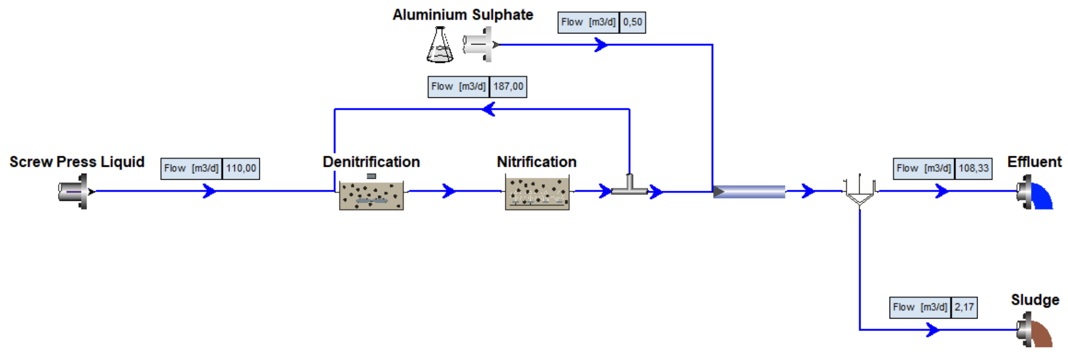


Figure 14: Biowin model for uncertainty analysis scenario: Supernatant treatment.

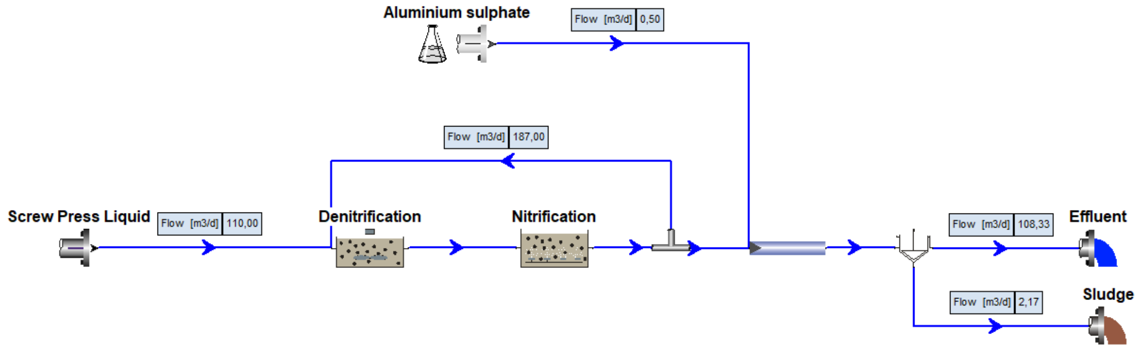


Figure 15: Biowin model for uncertainty analysis scenario: Worst efficiency of primary treatment.

4.3.3.4 Variations in flow rates

The wide range of flow rates, varying from 6 to 600 m^3/day based on scaling the data from the NEST, results in a fivefold increase (or decrease) (**Table 11**) in the size of the treatment unit and its power requirements. This is expected as the baseline scenario considers a flow rate of 110 m^3/day. Flow rates from other urban communities are typically 0.5 to 1.5 times (**Table 11**) the average flow rate observed in the NEST, further affecting treatment unit sizing. Such fluctuations can impact downstream performance, making it impractical to base system design solely on average flow rates. Hence, installing an equalization tank is recommended to manage these variations and ensure more consistent flow rates, thereby enhancing treatment performance in downstream units. Additionally, since blackwater generation fluctuates throughout the day, an equalization tank allows plant operators to efficiently control loading to the MBBR, preventing instances of under or overcapacity. It should also be noted that the average flow rate derived for other urban communities in different countries (min: 50, max: 150, average: 100, see **Appendix 7**) is similar to that scaled up from the NEST (110 m^3/day) meaning that the results produced in this uncertainty analysis are also, in general, applicable to other pure residential communities.

Therefore, an uncertainty analysis was performed considering different scenarios such as co-treatment of greywater with blackwater, degree of urine separation, and change in efficiency of primary treatment. The results show that blackwater treatment could be simplified with better urine separation however, this has consequences for the complete non-sewered system. In addition, the results also demonstrated the robustness of an MBBR to handle highly variable influent blackwater composition and provided a process design to practice wastewater reuse in already constructed urban communities (scenario: co-treatment of greywater and blackwater).

4.3.4 Carbon footprint analysis

Having developed technical designs, the next step was to quantify the carbon footprint of the proposed designs. The carbon footprint of the blackwater reclamation unit was calculated. This includes an equalisation tank, flocculation using CP314, a screw press, a moving bed biofilm reactor, chemical precipitation for phosphorous removal, ultrafiltration, granular activated carbon, and UV disinfection as defined in **3.3.1 Static modelling**. Additionally, the carbon footprint a complete non-sewered sanitation system, that encompasses separate treatment units for brownwater (assumed 90% urine separation), greywater, and urine, was also evaluated.

4.3.4.1 Carbon footprint of blackwater reclamation unit

The carbon footprint of the blackwater reuse unit was calculated following the methods described in **3.3.4 Carbon footprint analysis**.

Figure 16 shows the carbon footprint of a system serving 2000 residents assuming it is installed in different countries. Burkina Faso represents a low-income country; India and China represent middle-income countries, and United States of America and Switzerland are high-income countries. However, income level does not correlate with carbon footprint. Instead, the carbon footprint is primarily governed by the energy mix, as discussed in the following paragraphs.

The carbon footprint ranges from 1.5-3 $kgCO_2\text{-}e/m^3_{\text{treated blackwater}}$ depending on the country in which the system was assumed to be be installed. The total footprint varies between countries due to the Scope 2 emissions from electricity consumption. The largest contributor to the carbon footprint were the Scope 2 emissions from electricity consumption for all countries except Switzerland where the largest contributor were the Scope 1 nitrous oxide emissions.

The carbon emissions from the consumption of electricity (Scope 2) are lowest for Switzerland since electricity production in the country is dominated by nuclear and hydropower (90%) that are considered to be low-carbon sources of electricity. As opposed to this, the primary contributors to electricity production in other countries are fossil fuels: Burkina Faso (50%), India (72%), China (63%), and United States of America (60%) (IEA, 2024). Thus, the carbon footprint of the system, in general, would be low in countries where electricity is produced from low-carbon sources.

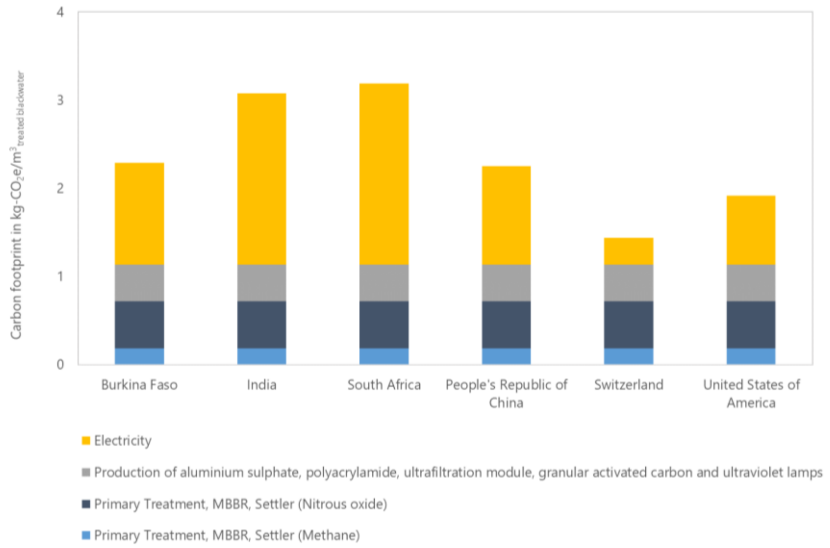


Figure 16: Carbon footprint of blackwater reclamation unit in $kgCO_2\text{-}e/m^3_{\text{treated blackwater}}$ assuming installation in different countries.

Direct N_2O emissions (Scope 1) were calculated using emission factors from full-scale sewered treatment plants since no data was available for non-sewered settings. It is possible that in non-sewered systems these emissions are higher since process conditions (e.g., dissolved oxygen, influent nitrogen load) heavily impact nitrous oxide emissions and it more difficult to control these parameters in small-scale systems due to more variable inflow wastewater (Law et al., 2012). N_2O is a known intermediate during denitrification and a by-product formed by ammonia-oxidizing bacteria during nitrification (Law et al., 2012). Variable process conditions will affect the rates of denitrification and nitrification and therefore the total N_2O emissions. Previously, it was estimated that a 1% increase in the nitrogen load (e.g., increase from 1% to 2%) that is converted to N_2O could increase the total carbon footprint of a sewered wastewater treatment plant by 30% (Boiocchi et al., 2023). Therefore, it is important to accurately monitor process conditions in non-sewered settings to manage the nitrous oxide emissions.

Indirect Scope 3 emissions from production of chemicals and technologies are also significant for the non-sewered system. These emissions were possibly underestimated since emissions from transport of materials were not considered. The contribution of Scope 3 emissions to the total carbon footprint is in contrast to sewered systems where the largest contributor were, 1) indirect emissions from electricity consumption, or 2) direct CH_4 and N_2O emissions depending on treatment technology and the country of installation (Delre et al., 2019; Friedrich et al., 2009; P. Singh et al., 2016; Wu et al., 2022; X. Zhou et al., 2022). This means that for non-sewered systems it is important to quantify not only Scope 1 and Scope 2 but also Scope 3 emissions for accurate estimation of the carbon footprint.

The CH_4 emissions from the system are low because of the system boundary considered and the choice of technology. The largest contributors to the CH_4 emission in wastewater treatment are anaerobic sludge digestion processes followed by emissions due to anaerobic conditions in sewer pipes. Since these components were not a part of the system boundary, the CH_4 emissions seem to be low. In addition, the choice of non-sewered technology considered also affects the CH_4 emissions. Pit latrine and septic tanks combined with constructed wetland have shown to emit higher fraction of CH_4 as compared to N_2O (Cheng et al., 2022; Risch et al., 2021). However, the technologically configuration considered here (MBBR) does not include any long-term storage. It is therefore assumed, that conditions for anaerobic digestion are not achieved and thus CH_4 emissions were negligible.

4.3.4.2 Carbon footprint of a complete non-sewered sanitation system

In the previous section, the carbon footprint of the blackwater reclamation unit was calculated. However, the blackwater reclamation unit is not a complete non-sewered sanitation system as greywater and urine that were collected separately must also be treated before being reused or discharged. Therefore, the carbon footprint of a complete non-sewered sanitation system serving 2000 residents consisting of separate treatment units for greywater, blackwater and urine was calculated. The assumption was that 90% of the urine was collected separately from brownwater using urine-separating toilets. These calculations serve as a valuable guide to understanding the primary contributors to the carbon footprint, providing insightful direction for GHG emission mitigation strategies without being a comprehensive assessment.

The results of the calculations are presented graphically in **Figure 17**. The left graph represents the carbon footprint of the non-sewered system including a distillation unit, where urine is concentrated to reduce liquid volume, facilitating transport and use as fertilizer. The right graph shows the carbon footprint without the distillation apparatus.

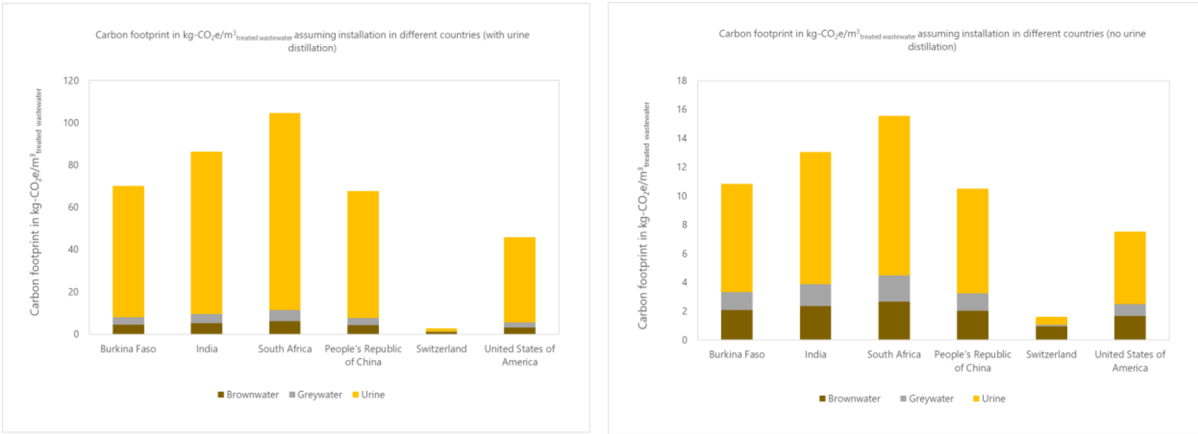


Figure 17: Carbon footprint of a complete non-sewered treatment system consisting of brownwater (90% urine separation), greywater, and urine treatment. The left graph shows the carbon footprint including urine concentration using distillation. The right graph shows the carbon footprint excluding the distillation apparatus.

The largest source of emissions are the indirect CO_2 emissions due to electricity consumption in distillation. The distiller consumes an energy of approximately 107 Wh/L_{urine} (or 107 kWh/m^3) (Faust et al., 2022) which is much higher than the energy consumption from all other units, e.g., aerators and pumps used for greywater, brownwater or urine treatment (~20 kWh/$m^3_{\text{treated wastewater}}$). This is also much higher than the energy consumption in sewered wastewater treatment plants which ranges from 1-10 kWh/m^3 (Olsson, 2012). This explains the exceptionally high carbon footprint of the non-sewered system in all countries considered except Switzerland. The primary reason is that electricity production in these countries relies heavily on fossil fuels, leading to significantly higher carbon emissions. Therefore, in countries where electricity production is primarily based on fossil fuels, the carbon footprint of a non-sewered system incorporating urine distillation is significantly higher compared to other non-sewered or sewered sanitation systems.

If the distillation apparatus is not included in the system boundary (**Figure 17**, right), the carbon footprint reduces by 85% and varies from 2-16 kgCO_2-e/$m^3_{\text{treated wastewater}}$. While Switzerland is an outlier, the carbon footprint of the system in this case is similar to the footprint reported by Badeti et al. (2024) (25 kgCO_2-e/$m^3_{\text{treated wastewater}}$) which is one of the only studies that evaluates the carbon footprint of a non-sewered system including urine treatment (and not only urine separation). Badeti et al. (2024) used a side-stream MBR for treatment of 90% of the urine and a main-stream MBR to treat the rest of the wastewater. The carbon footprint was calculated for a lab-scale reactor of capacity 25 m^3 which was operated for 140 days. The authors mention that they did not consider urine concentration but recommended to include it in future studies.

Several authors have previously evaluated the impact of urine separation on the carbon footprint of a wastewater treatment plant, however these studies do not include the urine treatment technology while calculating the footprint which is misleading. For instance, Badeti et al. (2021) concluded that with 90% urine diversion, 98% of the N_2O emissions could be reduced but they did not include the emissions from urine treatment in their evaluation for carbon footprint. Therefore, this thesis examines the impact of both urine diversion and urine treatment on the total carbon footprint of wastewater treatment.

4.3.4.3 Comparing sewered and non-sewered sanitation concepts

Compared to sewered wastewater treatment, the carbon footprint of the non-sewered system is higher primarily because small treatment systems have higher energy consumption than larger systems (P. Singh et al., 2016). As the carbon footprint was primarily driven by energy consumption (except in countries with low-carbon electricity production, e.g., Switzerland), it is expected that small systems have a higher carbon footprint. Previously reported carbon footprint for sewered plants are shown in **Table**

12. All studies except Friedrich et al. (2009) did not include the carbon footprint due to construction of sewers in their evaluation which could be one reason why the footprint is lower than that of non-sewered sanitation concept.

Table 12: Literature review of carbon footprint of sewered sanitation concepts compared with the results from this study.

Carbon Footprint ($kgCO_2$-e/m^3)	**Location**	**Source**
3-105	Multiple Theoretical calculations for a hypothetical urban community of 2000 residents in different countries (including urine distillation)	This study
2-16	Multiple Theoretical calculations for a hypothetical urban community of 2000 residents in different countries (excluding urine distillation)	This study
0.603	China	X. Zhou et al. (2022)
0.653	South Africa	Friedrich et al. (2009)
0.56-5.22	India	P. Singh et al. (2016)
0.78-3.04	UK	P. Singh et al. (2016)
1.1-1.42	Calculated based on Activated Sludge Model developed by IWA	Flores-Alsina et al. (2011)
5.96	Australia	Chong et al. (2013)
1-1.5	45 different process configurations (e.g., ASP, UASB etc. combined anaerobic disgestion or landfills) considered	Wu et al. (2022)

Although the carbon footprint of the non-sewered is higher, proven strategies exist to reduce it. For instance, considering a hypothetical green electricity mix of 50% solar and 50% wind-energy (Emission Factor: 0.026 $kgCO_2$-e/kWh (Faust et al., 2022)) for all countries except Switzerland, the carbon footprint can be reduced by 90-95% as show in **Figure 18** even with urine distillation. The carbon footprint in case of Switzerland is still lower because the emission factor for electricity production in Switzerland is 0.013 $kgCO_2$-e/kWh which is half that of the hypothetical renewable energy mix considered. The emission factor for Switzerland is lower because electricity production is dominated by nuclear energy (53%), hydro power (22%), and biofuels (22%) (IEA, 2024).

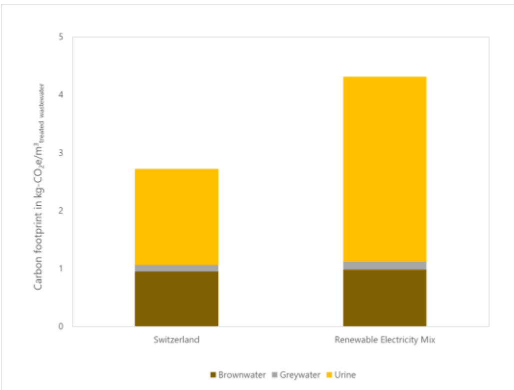


Figure 18: Carbon footprint ($kgCO_2$-e/$m^3_{treated\ wastewater}$) of the complete non-sewered sanitation concept assuming it is powered with a hypothetical renewable energy mix (Emission Factor = 0.026 $kgCO_2$-e/kWh) compared to the carbon footprint of the same system when installed in Switzerland.

Although this is a hypothetical scenario, it shows that if non-sewered systems were powered using renewable energy (partly or completely), non-sewered sanitation could be a viable supplement to sewered sanitation without compromising environmental sustainability in terms of GHG emissions. In addition, process control strategies may be utilised to reduce the footprint. For example, Faust et al. (2022) show that with better process control that limits the nitrite concentrations below 5 mg/L and by excluding intermediate storage units, the nitrous oxide emissions from urine treatment can be reduced by up to 30%.

Despite the higher carbon footprint, several benefits of non-sewered sanitation systems were observed. Firstly, CH_4 emissions are negligible due to reduced storage times. The carbon footprint can be significantly reduced by utilizing renewable energy sources. Additionally, the studies considered in **Table 12** did not account for emissions from the construction of sewered plants, which would be considerably higher compared to non-sewered systems. With resource recovery, emissions can be further reduced by accounting for the avoided burdens. Therefore, several benefits could be achieved from non-sewered sanitation when compared with sewered treatment plants with respect to environmental sustainability.

The estimates of GHG emissions from the non-sewered system are largely based on assumptions, and emission factors derived from sewered treatment plants. The actual GHG emissions might differ across treatment capacities and scales and could be influenced by the influent wastewater characteristics and local conditions. Therefore, the results should be used only as a preliminary guide. Further direct measurements of CH_4 and N_2O are needed to validate the calculated values for assessing the sustainability of non-sewered sanitation. In addition, several components were excluded from the calculations, such as pipes used for wastewater transport and the transport of chemicals. These factors should also be quantified by other researchers. Nevertheless, an estimate of the carbon footprint of a non-sewered sanitation system was provided.

4.4 Feasibility study

The final part of the thesis focuses on evaluating the applicability of the results and methods developed for the hypothetical urban community to the NEST building (a wastewater research facility) and to other urban communities in low-, middle-, or high-income countries. This involves a detailed discussion of the adaptability and scalability of the proposed system.

In addition, modifications were made to the theoretical designs developed in **3.3 Static modelling and environmental sustainability** to adapt it for pilot testing by future researchers in the NEST. The proposed process design is conveyed through a piping and instrumentation diagram created using PowerPoint. This diagram provides a visual representation of the proposed system layout and equipment arrangement, facilitating a clearer understanding of the design.

4.4.1 Considerations for implementation in NEST

The treatment systems designed for potable and non-potable water reuse in the hypothetical urban community were presented to experts at Eawag. Details about these experts were provided in **3.3.2 Selecting one reuse category**. The experts concurred that non-potable reuse is the most suitable option for a pilot test at NEST, considering factors such as the demand for recycled water and operational simplicity (see also **4.3.2 Selecting one reuse category**). The following sections will discuss how the design outlined in the previous sections can be adapted for implementation at NEST.

4.4.1.1 Process design

The adapted process design for pilot testing at NEST is shown in **Figure 19**, with the underlying assumptions and decisions outlined in the following paragraphs.

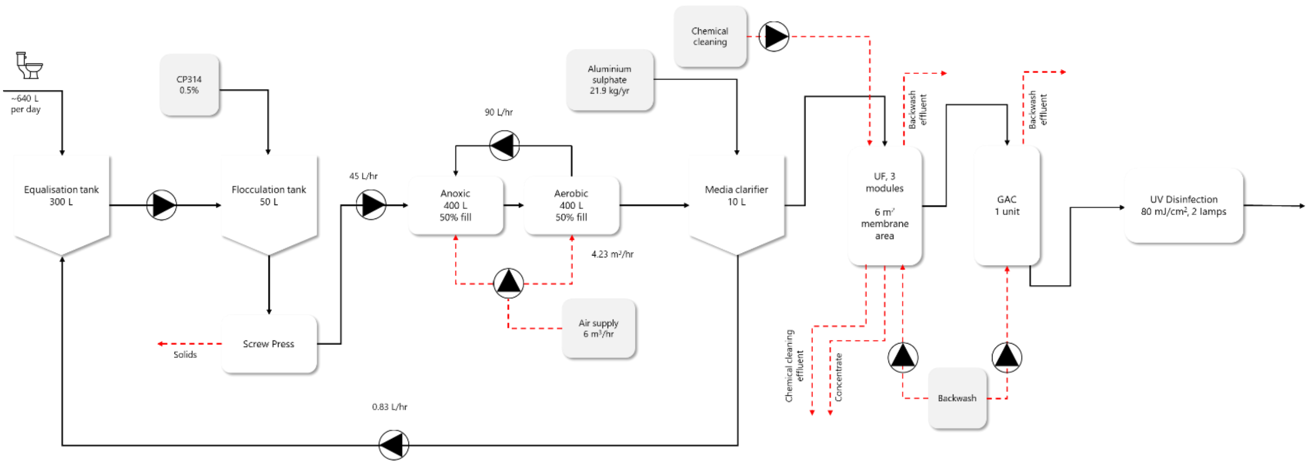


Figure 19: The schematic depicts a proposed process design for blackwater reclamation intended for non-potable applications, which future researchers will pilot test at NEST.

Assumptions. The unit sizing of treatment units downstream of the screw press is based on the assumption of a minimum flux required to achieve optimal recovery during ultrafiltration. This flux was assumed to be 2.5 L/m^2-h and was derived from the existing greywater unit at NEST, which handles 1600 L/day using six ultrafiltration membrane modules. It was estimated that three membrane modules would be necessary to handle the influent blackwater flow, previously measured to be approximately 640 L/day (**Appendix 9**). This results in a flow rate of 45 L/hour[1] that should enter the ultrafiltration membrane, which was also set as the design flow rate for treatment units downstream of the screw press.

Secondary treatment. The MBBR was sized according to an influent flow rate of 45 L/hour and flow-weighted average concentration of the screw press liquid (**4.1.2 Water quality**). The ISO 30500:2018 standard (ISO, 2018) was used to determine the effluent quality. For reference, ISO standard specifies the following effluent quality target for the entire non-sewered sanitation system: TSS: 30 mg/L, COD: 50 mg/L, TN = 70% removal, TP = 80% removal (**Table 4**). Due to the lack of data on greywater and urine quality, the ISO standard was assumed to apply only to the blackwater system, and the required effluent quality for TN and TP was determined accordingly. Separation from toilet was also not considered as data was unavailable. Retention times in the MBBR were calculated to be 1.2 hours each in the aerobic and anoxic zones based on BioWin modeling, which were then used to determine the optimum capacity of the equalization tank.

Primary treatment. Blackwater enters the existing 130 L equalization tank at NEST, followed by the flocculation tank (50 L) and the screw press, which together provide primary treatment. However, the equalization tank's capacity was found to be insufficient to handle peak flows, considering the hydraulic

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[1] Flux (2.5 L/m^2-h) × Number of membranes (3) × Area of each membrane (6 m^2)

retention time calculated for the MBBR in the previous paragraph. Table 13 shows that during peak times (10:00 – 17:30), the tank fills to 130 L in 1.5, 2.5, 3.5 hours, which would quickly overload the MBBR, where the hydraulic retention time is calculated to be 2.6 hours. To address this, either the equalization tank capacity must be increased or an additional buffer tank should be added after the screw press. Here, it was assumed that the capacity of the existing equalization tank is increased, recalculating it to be 300 L.

Table 13: Time required to fill in 130 L in the equalisation tank based on data collected from NEST on 29 February, 2024 over 24 hours.

Time slot	Number of hours to fill 130 L
12:00 – 10:00	10
10:00 – 11:30	1.5
11:30 – 14:00	2.5
14:00 – 17:30	3.5
17:30 – 23:59	6.5

Tertiary and advanced treatment. Solid-liquid separation after the MBBR is accomplished using a media clarifier as discussed in **4.3.1.1 Reuse category 1 and 2 (Non-potable reuse)**. The hydraulic loading of a media clarifier was assumed to be 2.2 m^3/m^2-h (Nof et al., 2024) to calculate the capacity of the media clarifier. Sludge from the media clarifier is recycled back to the equalization tank, from where it is dewatered in the screw press. This process removes solids contributing to total COD, nutrient and TSS removal from influent blackwater, fulfilling the goals of secondary treatment. This approach avoids the added complexity of installing sludge dewatering systems. Note that this is not an IFAS configuration, as the suspended biomass is not intentionally reintroduced into the MBBR. The chemical demand for phosphorous precipitation includes 100 g/day aluminum sulfate, equivalent to 21 kg/year. Chemical demand is low, and dosing can be managed similarly to CP314 dosing during flocculation. The area of the GAC and the UV dosage were calculated using the assumptions and equations presented in **Appendix 6**.

4.4.1.2 Considerations and recommendations

To enhance the process design and simplify pilot testing for blackwater reuse in the NEST, several key considerations and recommendations should be addressed.

Define water reuse goals and standards. The process design should be tailored according to specific reuse applications. For instance, if the blackwater is intended for infiltration into groundwater, a lower dose of UV treatment may suffice. It is crucial to ensure that the design adheres to relevant standards. While the current design complies with ISO standards, these are based on pathogen targets for human contact and may not directly apply to Switzerland. Therefore, selecting appropriate local targets and verifying that the process design meets these targets is essential. The present design is suitable for applications such as infiltration in blue-green infrastructure or construction water, provided ISO standards are used for compliance.

Increase urine separation. Enhanced urine separation simplifies the blackwater reuse process by meeting nutrient removal targets through source separation (**4.3.3.2 Urine separation**). This removes the chemical demand for phosphorous precipitation. Given that the NEST already has a urine treatment and concentration system, it is advisable to increase urine separation before pilot testing blackwater reuse. This approach makes the design more applicable to other communities with effective source separation practices. Additionally, increased urine separation allows for the use of simpler technologies, such as vermifiltration, instead of MBBR, saving energy, and capital costs (**4.3.3.2 Urine separation**).

Co-treatment with greywater. To maximize the amount of water available for reuse from NEST, consider co-treating the blackwater left after the screw press with the existing greywater system, which is currently underutilized. Assess the available capacity for blackwater treatment within the greywater system and discuss the feasibility of co-treatment. This evaluation should determine whether the design is replicable in other urban communities and weigh its pros and cons. Co-treatment with greywater could also be a viable alternative if there is insufficient space to install a new blackwater reuse unit in the NEST.

Alternative to chemical dosing. Although aluminium sulfate was considered for chemical dosing, electrocoagulation is another potential option. Experiments are needed to determine the optimal charge dosage and rate for effective flocculation of blackwater. Previous studies have shown success with electrocoagulation for blackwater (and greywater) (Aburto Vazquez, 2023; Gogoi et al., 2023; Talekar et al., 2018; J. Xu et al., 2023b), but results may not be directly transferable due to varying characteristics of blackwater in the NEST. In addition, the liquid after MBBR has a higher fraction of small colloidal matter, which may be challenging to flocculate. Therefore, conducting experiments to validate electrocoagulation as an alternative to chemical dosing is necessary before implementation in NEST.

By considering these recommendations, the process design for blackwater reuse in the NEST can be optimized for simplicity, compliance, and broader applicability.

4.4.2 Outlook for other urban communities

The solutions presented in the previous sections were specific to a hypothetical urban community surrounding the NEST and the NEST in particular. This section explores the applicability of the results to other urban communities and demonstrates how to apply the methodology to produce unique solutions for blackwater reclamation in these settlements.

Low-income countries

In low-income countries, only 20% of the urban population is served by water-based sanitation systems (e.g., flush toilets), while the majority relies on dry sanitation methods (e.g., composting toilets) or open defecation. A primary consideration in these settings is assessing the practicality of domestic wastewater reuse, given the limited availability of wastewater. On the other hand, wastewater treatment is often neglected, with only 15% receiving treatment through sewer-based systems or fecal sludge management (UNICEF & WHO, 2023). Centralized or sewer-based wastewater treatment plants in these regions are typically overloaded, non-functional, or non-existent (especially in fragile and conflict-affected countries) (WaterAid, 2019). Consequently, non-sewered sanitation can provide an effective pathway to improving access to safely managed sanitation.

Common causes of failure for wastewater treatment facilities in low-income countries include high operation and maintenance costs, frequent power cuts, lack of sludge elimination capacity, lack of spare parts, limited qualified personnel, overcapacity, and overambitious effluent quality regulations. Simple technologies such as waste stabilization ponds often malfunction due to the lack of institutional capacity for sludge removal (WaterAid, 2019). Therefore, the previously discussed treatment train for blackwater treatment and reuse (MBBR, UF, GAC, UV) is not directly applicable in these settings because of high energy use and frequent maintenance requirements. Although certain technologies (e.g., membrane filters) are used in water treatment plants, their application for wastewater treatment in low-income countries is not documented (WaterAid, 2019). However, the method developed in this thesis can still be used to come to appropriate solutions for low-income settings.

The first and most important step would be to select effluent compliance standards and define reuse possibilities that can be confidently met in these settings, as discussed in **4.1.3 Reuse possibilities and effluent quality requirements**. For instance, in many low-income countries, untreated wastewater is used for high-value vegetable production in urban and peri-urban locations, posing serious health risks for both agricultural workers and consumers. The market demand for fresh produce grown near cities often overlooks these risks (Raschid-Sally & Parkinson, 2004). Thus, it is crucial to define appropriate reuse applications along with relevant standards that can reliably protect public health and the environment while being cost-effective.

Assuming a relaxed nutrient removal standard (as defined in **Table 6**) is selected and the reclamation unit will be installed underground, the following technologies could be selected using the pre-selection matrix presented in **4.2.1 Pre-selection**.

- Secondary treatment: Trickling filter, Rotating biological contactor, Upflow anaerobic sludge blanket/Trickling filter, Vermifiltration, Anaerobic filter, Anaerobic baffled reactor
- Tertiary treatment: UV disinfection, Chlorination, Polishing pond

Having selected appropriate technologies and configuring them into treatment trains, the decision-making criteria defined in **4.2.3 Decision-making criteria** can be utilised to select an appropriate treatment train. The weighting of the cirteria have to be set carefully according to the context. For example, in this settings with poor electricity supply, or high maintenance requirements, the decision-making criteria related to energy, and maintenance should be weighed higher since the most importance. This comparison will result in a treatment train that is most appropriate for the low-income setting to accomplish wastewater reuse.

Middle-income countries

In lower and upper middle-income countries, nearly 50-75% of the wastewater is treated via fecal sludge management or sewer-based systems, and 75-95% of the population is served by septic tanks or flush toilets connected to sewers (UNICEF & WHO, 2023). Therefore, wastewater reuse in these countries has significant potential. The reasons for the failure of treatment plants in these regions differ somewhat from those in low-income countries. While desludging and operation and maintenance (O&M) issues remain common, other problems include under capacity or over-capacity, abandonment, and inadequate financing models (WaterAid, 2019).

The choice of technology seems not a major hindrance in these countries (WaterAid, 2019). For instance, in India several fecal sludge treatment plants use MBBR followed by pressure sand filters, GAC and chlorination or UV for wastewater treatment (Vijayan et al., 2023). In Namibia, wastewater reclamation for drinking water production was established in 1969 and uses technologies such as activated sludge, rapid sand filtration, ultrafiltration, granular activated carbon and chlorination (Gerrity et al., 2013). However, the lack of adequate financing can hinder procurement as well as increase O&M costs which need to be borne by the users (Onu et al., 2023). Therefore, alternatives to ultrafiltration especially may be explored in these contexts for blackwater reclamation. This is discussed further in **6 Recommendations**.

In addition to the above considerations, source-separation of urine in middle-income countries requires careful assessment. For instance, in the municipality of eThekwini, South Africa, Roma et al. (2013) found a very low satisfaction with urine-diverting toilets after 10 years of implementation due to the smell in the toilets and malfunctioning of the pedestal. Therefore, the technology employed for urine diversion plays a crucial role in success of non-sewered sanitation. Additionally, in urban areas, transporting urine to agricultural sites may not be practical, necessitating its concentration to reduce volume (Larsen et al., 2009). This process involves a high energy requirement and significant carbon footprint, as demonstrated in **4.3.4 Carbon footprint analysis**. Therefore, while greywater and blackwater separation could be implemented in new urban settlements, achieving widespread acceptance and scalability for urine separation may take several years.

In middle-income countries, it is essential to first evaluate whether source separation is feasible and environmentally sustainable. Based on this assessment, an appropriate technology and treatment train can then be selected and designed using the methodology developed in this thesis, as well as the results from the uncertainty analysis.

High-income countries

In high-income countries, about 85% of the population is connected to sewers. Nonetheless, non-sewered sanitation can offer sustainable alternatives as sewer-based infrastructures approach the end of their lifespan or reach capacity (Shaw et al., 2021). Non-sewered treatment systems, such as the johkasou systems in Japan, are successfully being applied on a larger scale today and are also being implemented at new construction sites, particularly in high-density areas of European Union countries and the USA (Eggimann, 2016). Additionally, decentralization serves as an alternative for addressing some of the ecological limitations of the established centralized approach, such as leaking pipes and combined sewer overflows (Eggimann, 2016). Stringent discharge laws necessitate more extensive wastewater treatment, which could be more expensive than reuse providing further support for wastewater reuse (US EPA, 2012).

In addition, even in countries with a high degree of centralization, non-sewered infrastructures could still be a viable alternative, especially when local reuse is desired. In distributed or upcoming urban settlements, rather than connecting all houses directly to a sewer, an optimal degree of decentralization may be determined as suggested by Eggimann (2016). For instance, in Trubschachen (~1500 inhabitants, 365 buildings) in the Emmental region of western Switzerland, 85% centralisation was more cost-effective than 100% centralisation due to the challenging topography of the region and the urban population distribution (Eggimann, 2016). Sewer construction exhibits diseconomies of scale, meaning that in dense urban areas or challenging terrains, it might be advantageous to implement satellite systems where non-sewered systems provide local reuse and recovery. Apart from this, non-sewered systems can also provide redundancy and resilience in sensitive or water-scarce regions especially in the face of climate change.

Urine source separation using No-Mix technology has already shown high acceptance in several European countries (Lienert & Larsen, 2010). However, public acceptance of crops irrigated with human feces or urine remains a concern, and the logistics of urine transport pose additional challenges (Larsen et al., 2009). In addition, not all countries permit the use of products recovered from wastewater. For instance, the European Union allows the application of sludge and urine in agriculture (European Commission, 2024; European Union, 2024), whereas Switzerland bans the use of sludge for agricultural applications (Federal Department of the Environment, 2003). However, the use of urine fertilizer is permitted in Switzerland. For example, Aurin, a urine-based fertiliser, has been approved by Swiss authorities, and has shown high acceptance amongst farmers (Eawag, 2016). Therefore, legislation needs to co-evolve with non-sewered sanitation systems to maximize their benefits in high-income countries. Often, the timeline for implementing legislation is much longer than the development of technology, which can render non-sewered sanitation less useful in these settings. Nonetheless, water reuse could still be implemented and the results from the uncertainty analysis (**4.3.3 Uncertainty analysis**) can be used to design a non-sewered system.

The treatment trains designed for the hypothetical urban community can be replicated in other high-income countries since technology availability is not the limiting factor. For example, in Germany, blackwater and greywater separation and treatment have proven effective for biogas production and reusing water for industrial purposes (Schelbert, Luthi, & Binz, 2023). In northern Europe, several pilot plants with source-separating systems have been proposed, focusing on nutrient, heat, or water recovery as listed in **2.2 Community scale blackwater reclamation**.

Conclusions & Recommendations

5 Conclusions

In this chapter, general conclusions from the thesis are presented followed by answers to the research questions.

5.1 General conclusions

The provision of clean water and safely managed sanitation is a pressing global challenge (UNICEF & WHO, 2023), which can be alleviated by practicing water reuse and complementing sewered sanitation with non-sewered alternatives. Reclaiming blackwater in non-sewered sanitation systems is a growing research area where a gap exists on how to select appropriate technologies along the treatment train to meet reuse goals. Therefore, this study proposed a methodology to facilitate this process and simplify the comparison and selection of suitable technologies for blackwater reclamation. Using this framework, researchers and practitioners can design non-sewered sanitation systems to keep pace with rapid urban expansion, and shrinking water resources amidst the challenges of climate change.

The selection of appropriate technologies was performed using pre-selection and decision-making criteria. These globally-relevant criteria ensure that the chosen treatment technologies are economically, socially, technically, and environmentally sustainable in various urban settings (for e.g., an apartment building or a small urban community). The selection process was followed by static modelling conducted using BioWin, providing a basis for pilot testing. Pilot testing is crucial for understanding how theoretical results translate in the field, given the high variability in blackwater composition. The design calculations, therefore, offer insights into potential challenges that may be encountered during pilot testing.

The thesis also highlights the advantages and disadvantages of source separation through a carbon footprint analysis. Previously, the carbon footprint of a complete non-sewered sanitation system, including urine treatment and concentration, has not been quantified. This research provides a starting point for other researchers to conduct a complete life cycle analysis to assess the environmental sustainability of non-sewered sanitation. Quantifying this sustainability is important to develop a holistic understanding of water reuse and resource recovery in small urban communities.

As some findings from this research may primarily apply to middle and high-income countries, a similar study tailored for low-income countries should be conducted. Furthermore, this thesis fosters opportunities for cross-disciplinary connections, addressing knowledge gaps such as clarifying the applicability of effluent standards for recycling systems and development for effluent standards that are widely applicable and achievable. For instance, the ISO standard for non-sewered sanitation systems is the only globally applicable standard for such systems, but it does not clarify whether it also applies to fully recycling systems. Additionally, international standards often define effluent compliance targets for broad reuse categories (rather than for specific reuse applications), leading to the over-design and under-design of non-sewered systems. Addressing these discrepancies and knowledge gaps can enhance the implementation and adoption of non-sewered systems. Further research should also explore the quantification of Scope 1 and 3 GHG emissions from non-sewered systems, an area currently lacking in literature but of considerable significance, as evidenced by the findings from this study.

Growth in scientific research on non-sewered sanitation must go hand in hand with the development of operational knowledge to bring it to the same maturity level as sewered sanitation (Strande, 2024). This presents opportunities for collaboration between academia and industry to drive innovation. Implementing non-sewered sanitation also encourages city planners to consider source separation and water reuse, which can be crucial for developing climate-resilient and sustainable sanitation systems. Moreover, as the need arises to reconstruct, refurbish, or upgrade aging centralized systems, governments might find it valuable to explore alternatives to traditional wastewater treatment methods. This exploration could support the coexistence of various degrees of centralization and decentralization, including satellite systems (Eggimann, 2016). By considering these diverse approaches, we can create more flexible and resilient sanitation infrastructures that can better adapt to changing environmental and urban conditions.

5.2 Answers to research questions

What treatment trains are most suitable for reclaiming blackwater following dewatering with flocculants and a screw press?

The optimal treatment train for blackwater reclamation varies depending on the context and intended reuse applications. In a high-income country like Switzerland, for instance, different treatment trains were recommended based on whether the reclaimed water is used for non-potable or potable purposes.

- For non-potable applications such as toilet flushing, the suggested treatment sequence following the dewatering unit (equalisation tank, flocculation, screw press) includes, MBBR, Electrocoagulation, UF, GAC, and UV disinfection.
- For potable applications, such as swimming, a more comprehensive treatment train is required. This includes, MBBR, Electrocoagulation, UF, NF, GAC, and UV disinfection.

These recommendations were developed considering a hypothetical scenario of an urban community comprising 2,000 residents located around the NEST building in Switzerland. The scenario assumes the community practices separate collection and treatment of greywater and blackwater, with some homes retrofitted with urine-diverting toilets. The most suitable treatment train may vary for different urban communities, as discussed in the **4.4.2 Outlook for other urban communities**.

What data is required to design a treatment train for blackwater reclamation?

For preliminary design studies, it is imperative to define several key factors.

- First, understanding blackwater characteristics and flow rates is crucial, as this information will influence the sizing of the treatment units.
- Second, identifying potential reuse possibilities is essential. The intended applications for the treated water, whether for non-potable uses such as irrigation and toilet flushing or potable uses such as swimming and drinking, will determine the required treatment level (secondary, tertiary, or advanced treatment).
- Third, ensuring that the treated effluent meets compliance standards is a critical aspect of the design process. Compliance standards should be selected such that they are achievable in the local contexts. While regulatory bodies such as WHO, US EPA and ISO set standards for water reuse, it is not necessary that these standards can be met reliability in all urban communities where access to certain technologies and expertise may not be possible.
- Lastly, the amount of space available for the treatment system and the decision on whether it will be installed underground or above ground are important design considerations.

For more detailed design studies additional consideration would be:

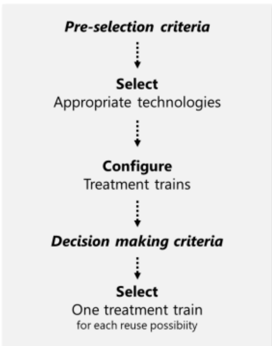
- The annual pattern of blackwater generation. Understanding how wastewater flow varies throughout the year is vital for designing a system that can handle peak loads and operate efficiently during periods of low flow.
- Another critical factor are the local laws that the engineering design must comply with. These laws can dictate specific treatment processes, performance standards, and reporting requirements.

Ensuring compliance with these regulations is necessary to avoid legal issues and ensure the system's long-term viability.

How can decision-making processes be used to select treatment trains for different reuse possibilities?

Selecting treatment trains for different reuse possibilities involves a structured decision-making process. The decision-making process adopted here is detailed below and a schematic representation is provided for reference.

- Although a wide array of wastewater technologies exists, not all are suitable for the specific requirements of non-sewered sanitation in urban areas. To narrow down the technology options, four pre-selection criteria were defined. These criteria help identify technologies capable of meeting various objectives, such as secondary, tertiary, and advanced treatment of wastewater. A pre-selection matrix was presented that allows for other researchers, engineers, or planner to select appropriate technology based on nutrient removal targets, location of the treatment plant and the scale of blackwater treatment.
- Once a set of appropriate technologies was selected, they were configured into complete treatment trains designed to meet the compliance standards set by the International Standards Organisation for non-sewered sanitation systems (ISO, 2018).
- The selection of the most suitable treatment train for a specific reuse possibility was guided by 14 decision-making criteria. While these criteria are relevant across all urban communities, their importance may vary depending on local conditions. Therefore, it is essential to consult local sanitation experts and community users to gather their opinions and insights. Data for the decision-making criteria can be sourced from academic research or local expertise, ensuring that the selected treatment train is both effective and contextually appropriate.



How can a static design model be used to select a suitable reuse possibility for pilot testing by future researchers?

It was demonstrated that BioWin can be effectively used to develop static models for non-sewered sanitation systems. Static modelling shows that the treatment train for non-potable applications occupies an area of 0.8-1 $m^2/m^3_{\text{wastewater treated}}$ and consumes 1-2 kWh/m^3 of electrical energy. For potable applications, the energy consumption increased to 3-5 kWh/m^3. Although these values are preliminary estimates, they were higher when compared to those of sewered sanitation systems (0.3-1 $m^2/m^3_{\text{wastewater treated}}$, 1-10 kWh/m^3) which presents opportunities for design optimisation.

These results were presented to sanitation experts, whose insights were utilized to select a suitable reuse possibility that could be hypothetically pilot tested in the urban community. Experts agreed that the Reuse Category 1 or 2 applications (non-potable reuse) would be the most suitable for pilot testing due to ease of operation, lower costs, and demand for recycled water when compared to Reuse Category 3 applications (potable reuse).

What is the carbon footprint of a complete non-sewered sanitation system?

Static modelling can be used to calculate the carbon footprint of a complete non-sewered sanitation system, which includes greywater, brownwater (90% urine separation), and urine treatment and concentration for fertilizer production. Direct CH_4 and N_2O emissions (Scope 1), Scope 2 emissions from electricity consumption, and Scope 3 emissions from material production were considered in the calculations, which were performed assuming installation in different countries.

The calculations show that the largest contributor to the carbon footprint were the indirect emissions from electricity consumption in countries where electricity production is predominantly from fossil fuels. The highest contributor to the footprint was electricity consumption in urine distillation, which concentrates urine for easier transport as fertilizer. However, in countries where the electricity production is due to low-carbon sources, e.g., Switzerland, the highest contributor to the total carbon footprint were direct nitrous oxide emissions during wastewater treatment.

The carbon footprint of a complete non-sewered sanitation system without urine concentration is ~20 kg CO_2-e/m^3, which is higher than that of conventional wastewater treatment (0.5-3 kg CO_2-e/m^3). This is mainly because energy consumption increases as the scale of treatment decreases. This comparison excludes Scope 3 emissions (e.g., due to transport of materials, or construction) and was based on several assumptions as highlighted in **3.3.4 Carbon footprint analysis**. Inclusion of Scope 3 emissions could increase the carbon footprint of sewered system considerably. Therefore, this comparison is intended as an indicative comparison to provide insights on reducing the carbon footprint, rather than a declaration that non-sewered sanitation is not environmentally sustainable when compared with sewered sanitation. Avoided burdens (for e.g., emissions avoided from reduced extraction of freshwater resources) were not included in calculations.

Assuming that the non-sewered treatment is powered completely using green electricity mix of 50% solar and 50% wind-energy (Emission Factor: 0.026 kgCO_2-e/kWh (Faust et al., 2022)), calculations showed that the carbon footprint could be reduced by 80%. Therefore, there is a realistic potential to decrease the carbon footprint of non-sewered sanitation systems, especially when installed in countries that rely on fossil fuel-based electricity production.

Can the suitable reuse possibility be implemented in the NEST and other urban communities?

The treatment train for non-potable applications (MBBR, Electrocoagulation, UF, GAC, UV) was deemed to be most suitable for the hypothetical urban community as well as for pilot testing by future researchers in the NEST. Although the treatment train may not be suitable for implementation in low-income urban communities because of the pre-selection and decision-making criteria that were adopted to select the treatment train, the the methodology developed as a result of this thesis (see answer to sub-research question 2) can be used to arrive at an appropriate solution. In middle- and high-income countries, the treatment train can be adopted as technological limitation are not abound however nuances of the specific urban community will determine the most appropriate solution.

The suitable reuse option can be implemented in the NEST as it is or with modifications based on increased urine separation, or co-treatment with greywater, were discussed in **4.4.1 Considerations for implementation in NEST**. Before pilot testing, the MEWS group is advised to define the reuse goals for the reclamation unit which will enable the selection and design of an appropriate process configurations discussed in **4.4.1 Considerations for implementation in NEST**.

6 Recommendations

6.1 Recommendations for developing appropriate standards

- Researchers and engineers should work in collaboration with regulatory bodies to redefine the boundary conditions (e.g., user-interface) applicable to effluent standards and to clarify the applicability of these standards for fully recycling non-sewered systems.

- Current monitoring requirements for non-sewered systems are derived from sewered plants and have proven to be cost-prohibitive in non-sewered contexts across all income settings (Reynaert et al., 2020a). Therefore, these requirements should be revised based on the practical experiences of implementing and operating non-sewered sanitation systems. It is hypothesised that adjusting these standards to reflect the unique challenges and realities of non-sewered systems will increase the feasibility of implementing non-sewered sanitation.

6.2 Recommendations for improving environmental sustainability

- While source separation presents opportunities for resource recovery, its environmental sustainability has not been fully quantified, particularly concerning the treatment of all wastewater streams. This study identified that urine treatment and concentration for fertilizer production significantly contribute to the total carbon footprint of non-sewered systems. Therefore, a complete life cycle assessment is required to further elaborate on these findings and quantify the costs and trade-offs of source separation and resource recovery. It is hypothesised that a complete life cycle assessment will enable generating insights on possible mitigation measures which can improve the environmental sustainability of wastewater reuse.

- Assessing whether the proposed treatment schemes can reliably be powered with renewable energy is paramount, especially in countries reliant on fossil fuels where the carbon footprint of non-sewered system may be high due to the electricity requirements. Evaluating the feasibility and scalability of renewable energy integration within these treatment schemes could be essential for long-term sustainability of non-sewered sanitation and wastewater reuse.

- Quantifying the contribution of Scope 3 emissions (e.g., emissions due to transport of materials, construction of sewers etc.) to the carbon footprint is crucial for a comprehensive understanding of the environmental impact of non-sewered treatment systems. Scope 3 emissions encompass indirect emissions generated throughout the entire lifecycle of the system, including those from the supply chain and end-user activities (Bartram et al., 2019). By quantifying these emissions, policymakers and stakeholders can identify areas for improvement and develop strategies to minimize environmental impact across the entire value chain.

- In this thesis, the avoided burden was not included in the carbon footprint calculations. For instance, wastewater reuse can avoid carbon emissions from freshwater extraction, which is an advantage of non-sewered systems. Therefore, these avoided burdens should be quantified to provide a holistic assessment of the pros and cons of non-sewered sanitation.

6.3 Recommendations for improving process design

- Ultrafiltration membranes, which function at high pressure to remove bacteria and viruses, are expensive to purchase and maintain (Peter, 2010). While gravity-driven ultrafiltration has shown promise for greywater treatment, it has not been tested for blackwater (Peter, 2010). Additionally, alternatives to ultrafiltration need to be explored, especially since these membranes are costly, and operators in low- and middle-income settings have accepted to intentionally by-passing these membranes during treatment to preserve their life and reduce energy consumption of treatment plant (WaterAid, 2019). More research is needed to identify viable alternatives and improve the affordability and effectiveness of blackwater treatment technologies. This will improve the cost-effectiveness of blackwater reclamation.

- One of the most crucial design parameters that can significantly impact plant performance is the dissolved oxygen (DO) levels. Higher DO levels can increase the demand for aeration, thereby affecting energy consumption. Insufficient DO concentrations can impact nitrification and denitrification which will significantly impact the nitrous oxide emissions adding to the carbon footprint (Bartram et al., 2019). Therefore, it is essential to evaluate and optimize possible DO concentrations in the design process. While some DO concentrations were tested during BioWin modelling, further optimization can enhance efficiency and reduce energy requirements.

- Currently, the proposed methods for removing phosphorus from blackwater involves chemical precipitation or electrocoagulation, both of which result in the production of metal complexes that render the phosphorus non-bioavailable. An enhanced biological phosphorous removal process configuration utilising an anaerobic MBBR has been pilot tested in Norway for municipal wastewater treatment, showing promise for biological phosphorus removal in attached growth treatment processes (Rudi et al., 2019). This method ensures that the phosphorus remains bioavailable in the solids and can be recovered if needed. However, no research exists on scaling down this technology for non-sewered sanitation. Therefore, the NEST can be used as a testing ground to scale down this innovative technology, aiming to implement it simply and reliably in non-sewered settings. This could be a simpler alternative when compared with other technologies that allow for phosphorous recovery in bio-available forms such as adsorption or crystallization (Melia et al., 2017). In addition, Austria, Germany and Switzerland have now made P recovery mandatory from municipal sewage sludge which provides further incentive to research this topic (European Sustainable Phosphorus Platform, 2024).

- In this thesis, polyacrylamide-based (PAM) flocculant was used. Although this flocculant forms strong flocs, the break-up of these flocs was observed due to the shear forces exerted by the screw press, which worsened the quality of the screw press liquid. If PAM were replaced with a bio-based conditioner, such as chitosan, known for forming weaker flocs, it is hypothesized that the quality of the screw press liquid would further deteriorate, complicating downstream treatment. Bio-based conditioners may be preferable when solids compositing or reuse is desired. However, it is also possible that the addition of colloidal solids due to the break-up of the flocs could improve denitrification performance, as denitrifiers have been shown to be quite efficient in utilizing colloidal solids through BioWin modelling (**4.3.3 Uncertainty Anaylsis**) improving the nitrogen removal performance. Therefore, the impact of shear forces from the screw press on floc break-up and downstream treatment should be evaluated when using other conditioners or a different screw press.

Appendix

Appendix

1 Literature review for blackwater treatment

The search query used for this literature review is shown in Figure 19 and conducted in the Web of Science search engine. The purpose of this query was to obtain a list of articles focused on blackwater treatment and reclamation. The search query resulted in 310 articles out of which only open-source were selected (122). The title and abstract of these 122 articles were reviewed and articles that did not focus on treatment technology or liquid reuse (instead focused on solids reuse) were removed. This resulted in 48 articles which are listed below Figure 19. The articles that focused on blackwater reuse were highlighted in Chapter 2.

Blackwater or Black water or Decentrali$ed or Off-site or Off-grid or On-site or Semi centralised	NEAR/3	Treatment or Reuse or Reclamation or Recyc$

Figure 20: Search query used for literature review for blackwater treatment and reclamation systems around the world

Results from search query

Skjelhaugen (1999)

Ham et al. (2007)

Sustainable Sanitation Alliance (2009)

Gallagher & Sharvelle (2010)

Otterpohl & Buzie (2011)

Spinosa et al. (2011)

Kumar et al. (2014)

Tervahauta et al. (2014)

Phan et al. (2015)

Vidya et al. (2015)

Jaffar Abdul Khaliq et al. (2017)

de Anda et al. (2018)

Mattos De Oliveira Cruz et al. (2018)

Reynaert et al. (2020a)

Sahondo et al. (2020)

Varigala et al. (2020)

X. C. Nguyen et al. (2020)

Davey et al. (2021)

Ferreira et al. (2021)

Lakho et al. (2021)

San Francisco Public Utilities Commission (2021)

Bahadur et al. (2023)

Kocbek et al. (2022)

El-Rawy et al. (2023)

Miorner et al. (2023)

Schelbert, Luthi, & Binz (2023)

Schelbert, Luthi, Binz, & Mitra (2023)

Schelbert, Luthi, Binz, & Miorner (2023)

Zhang et al. (2023)

Run4Life (2024)

2 Possible log reduction

Table 14: Range of possible log reduction for different pathogens that can achieved in selected unit processes. Data compiled from Chhipi-Shrestha et al. (2017), *and* (Tchobanoglous et al., 2013).

Treatment Technology	Bacteria	Virus	Protozoa	Helminths	Notes
Conventional Activated Sludge	1.5-1.95	1.25-1.92	0.75-0.98	<0.1	
Seqencing Batch Reactor	1.5-1.95	1.25-1.92	0.75-0.98	<0.1	Helminths, assumed same as conventional activated sludge
Extended Aeration	1.5-1.95	1.25-1.92	0.75-0.98	<0.1	Helminths, assumed same as conventional activated sludge
Membrane Bioreactor	6.1-6.73	3.25-5.01	7-7.9	2-6	Helminths, assumed same as microfiltration
Trickling Filter	1.5-1.95	1.25-1.92	0.75-0.98	1	
Rotating Biological Contactor	1.5-1.95	1.25-1.92	0.75-0.98	1	Helminths, assumed same as Trickling Filter
Moving Bed Biofilm Reactors	1.5-1.95	1.25-1.92	0.75-0.98	1	Helminths, assumed same as Trickling Filter
Submerged Aerated Fixed Film Reactor	1.5-1.95	1.25-1.92	0.75-0.98	1	Helminths, assumed same as Trickling Filter
Upflow Anaerobic Sludge Blanket/Trickling Filter	1.5-1.95	1.25-1.92	0.75-0.98	1	Helminths, assumed same as Trickling Filter
Depth Filtration	2.25-3.1	1.95-3.61	6.1-6.73	4	
Surface Filtration	0.5-0.95	0.25-0.47	0.5-0.95	0	
Microfiltration	1-4	0-2	1-4 (Cryptosporadi um). 2-6 (Giardia)	2-6	
Ultrafiltration	5-5.9	4.5-5.85	6.2-7.82	2-6	Helminths, assumed same as Microfiltration
Nanofiltration	3-6	3-5	>6	>6	
Reverse Osmosis	5.5-6.85	4.85-6.78	8-8.9	>6	
Chlorination	4-5.8	3-3.9	0.75-1.43	Negligible	
UV Radiation	3-3.9	2.12-3.81	3.5-3.95	Negligible	
Ozone	3.5-4.22	3-3.9	2-2.9	Negligible	
Granular Activated Carbon	0.6-1.05	0.45-0.67	2-2.63	Not defined	

3 Selection of decision-making criteria

Table 15: Selection process for decision-making criteria. Decision-making criteria from Spiller (2016) *are listed along with reasons why certain criteria were not adopted. Equivalent criteria from* Wingelaar (2023) *are listed for reference.*

Sr. No.	**Criteria from** Spiller (2016)	**Reason for removal**	**Equivalent criteria in** Wingelaar (2023)
1	Energy use	Selected	Resource use
2	Nutrient recovery/reuse	Not technology	Resource recovery potential
3	BOD/COD of effluent	Merged with criteria 'effluent quality'	System performance
4	Use of chemicals	Not technology	Reosurce use
5	Reuse water	Not technology	Resource recovery potential
6	Raw materials	Not technology	Resource use
7	Water use	Not technology	Safe product disposal
8	Discharge N and P to water	Merged with criteria 'effluent quality'	System performance
9	Sludge and waste production	Selected	System performance
10	Heavy metals to land	Not technology	Environment Friendly
11	Water self sufficiency	Not technology	
12	Pathogen removal/health	Selected	Community health
13	Emissions to air	Merged with criteria 'CO_2 eq. Emissions'	Environment Friendly
14	CO2 eq. Emissions	Selected	Environment Friendly
15	Energy recovery/production	Not technology	Resource recovery potential
16	River water quality	Not technology	Environment Friendly
17	Toxic compounds to water	Not technology	Environment Friendly
18	TSS removal	Merged with criteria 'effluent quality'	System performance
19	Sludge disposal to landfill	Not technology	Safe product disposal
20	Biodiversity	Not technology	Environment Friendly
21	Ground water quality	Not technology	Environment Friendly
22	Ground water quantity	Not technology	Environment Friendly
23	Odor/noise/insects/visual	Merged with criteria 'Impact of STP'	Nuisance, Aesthethics
24	Total water footprint	Not technology	
25	Reuse of organic compounds	Not technology	Resource recovery potential
26	Distance for transport of sludge	Not technology	
27	Impact on biodiversity	Not technology	Environment Friendly
28	Future demand for water	Not technology	
29	Acidification	Not technology	Environment Friendly
30	Certification on environmental issues	Not technology	
31	Certification of water quality issues	Not technology	
32	Total costs	Selected	Capital Expenditure, Operational expenditure
33	Affordability	Merged with 'Total costs'	
34	Cost recovery	Not technology	
35	Willingness to pay	Not technology	
36	Labour	Merged with 'Staffing requirement'	
37	Price of (water) waste treatment	Merged with 'Total costs'	
38	Asset management	Not technology	

39	Financial risk exposure	Not technology	
40	Awareness/participation	Not technology	
41	Acceptance (cultural)	Not technology	Cultural alignment
42	Competence and education required	Selected	Expertise required
43	Institutional capacity	Not technology	Policy alignment
44	Connected to drinking water supply	Not technology	
45	Social inclusion	Not technology	Ease of use
46	Water borne diseases and toxicity	Not technology	
47	Willingness to change behavior	Not technology	
48	Connected to water and sewerage service	Not technology	Cenralisation/Decentralisation
49	Climate change adoption measure	Not technology	
50	Local development	Not technology	Job opportunities
51	Water efficiency	Not technology	
52	Sustainable urban water management	Not technology	
53	Surface water supporting amenity of urban area	Not technology	
54	Existence and alignment of city planning	Not technology	
55	Accountability	Not technology	
56	Flexibility/Adaptability	Merged with 'Reliability/continuity of service'	Resilience
57	Land/space requirement	Selected	
58	Reliability/continuity of service	Selected	Resilience
59	Water loss/leakage/non-revenue water	Not technology	
60	Durability	Merged with 'Robustness'	
61	Staffing requirements	Selected	Expertise required, Robustness
62	Effluent quality	Selected	System performance
63	Robustness	Selected	Robustness
64	Drinking water quality	Not technology	
65	Impact of STP	Selected	Nuisance
66	Compliance to standards	Not technology	
67	Service interruptions	Merged with 'Reliability/continuity of service'	Resilience
68	Sewer flooding	Not technology	
69	Separate storm water management	Not technology	
70	Age of pipe infrastucture	Not technology	
71	Working conditions	Not technology	
72	Ease of construction	Selected	Locally available construction resources
73	Capacity of drinking water reserves	Not technology	
74	NA	Not technology	Geographic suitability

4 Qualitative data for comparing treatment trains

Data sources for developing personal professional expertise

Chhipi-Shrestha et al. (2017); Frankel (2022); Tare & Bose (2009); Tchobanoglous et al. (2013)

Table 16: Assigning data to qualitative indicators based on personal professional expertise and coding text data into numerical values. ASP = Activated sludge processes, MBBR = Moving bed biofilm reactor, MBR = Membrane bioreactor, UF = Ultrafiltration, NF = Nanofiltration, RO = Reverse osmosis, GAC = Granular activated carbon, CHLOR = Chlorination, UV = UV disinfection.

Text codes assigned to qualitative indicators based on personal professional expertise developed by reviewing textbooks and literature sources								
Treatment Technology	**Qualitative Indicators**							
	Sludge production	**Impact on health of staff/locals**	**Impact on surrounding building/properties**	**Number of skilled operator required**	**Level of expertise**	**Frequency of maintenance**	**Local availability of spare parts**	**Reliability**
ASP	High	Medium	Low	High	Low	Low	High	Medium
MBBR	Medium	Low	Low	Medium	Medium	Medium	Medium	Medium
MBR	Low	Low	Low	Low	High	High	Low	High
UF	NA	NA	NA	NA	NA	NA	NA	NA
NF	NA	NA	NA	NA	NA	NA	NA	NA
RO	NA	NA	NA	NA	NA	NA	NA	NA
GAC	NA	NA	NA	NA	NA	NA	NA	NA
CHLOR	NA	High	High	Low	Low	Low	High	NA
UV	NA	Low	Low	High	High	High	Low	NA
Coding the text values assigned above as numerical values based on whether a 'high' or a 'low' value is desirable for a given indicator								
Treatment Technology	**Qualitative Indicators**							
	Sludge production	**Impact on health of staff/locals**	**Impact on surrounding building/properties**	**Number of skilled operator required**	**Level of expertise**	**Frequency of maintenance**	**Local availability of spare parts**	**Reliability**
ASP	3	2	1	3	1	1	1	2
MBBR	2	1	1	2	2	2	2	2
MBR	1	1	1	1	3	3	3	1
UF	NA	NA	NA	NA	NA	NA	NA	NA
NF	NA	NA	NA	NA	NA	NA	NA	NA
RO	NA	NA	NA	NA	NA	NA	NA	NA
GAC	NA	NA	NA	NA	NA	NA	NA	NA
CHLOR	0	2	2	1	1	1	1	0
UV	0	1	1	2	2	2	2	0

5 Quantitative data for comparing treatment trains

Data sources for quantitative indicators (Land required, CAPEX, OPEX, Energy, GHG Emissions)

Brault et al. (2022a); Chhipi-Shrestha et al. (2017); Tare & Bose (2009); Tare (2011); Wang et al. (2022)

Table 17: Numerical data used for comparison of treatment trains for 14 decision making criteria derived. INR = Indian rupees, ML = Million litres, MLD = Million litres per day.

Treatment Technology	Land required	CAPEX	OPEX	Energy	GHG Emissions	Sludge production	Impact on health of staff/locals	Impact on surrounding building/properties	Number of skilled operator required	Level of expertise	Frequency of maintenance	Local availability of spare parts	Reliability	Quality
	m^2/m^3	million INR/MLD	million INR/year-MLD	kWh/ML	kgCO2-e/yr									
Activated sludge processes	2.00	3.20	0.40	202	5E+7	3	2	1	3	1	1	1	2	1
Moving Bed Biofilm Reactor	1.10	2.00	0.30	180	2.5E+7	2	1	1	2	2	2	2	2	1
Membrane Bioreactor	1.00	20.00	1.00	440	5E+7	1	1	1	1	3	3	3	1	1
Depth Filtration	1.00	10.00	0.80	140	0	0	0	0	0	0	0	0	0	0
Microfiltration	0.50	12.00	0.80	150	0	0	0	0	0	0	0	0	0	0
Ultrafiltration	0.50	15.00	0.80	180	0	0	0	0	0	0	0	0	0	0
Nanofiltration	1.50	17.00	1.50	500	0	0	0	0	0	0	0	0	0	0
Reverse Osmosis	1.50	18.00	2.00	1030	0	0	0	0	0	0	0	0	0	0
UV Treatment	0.00	6.00	0.10	60	0	0	1	1	2	2	2	2	0	0
Chlorine Treatment	0.00	6.00	0.70	23	0	0	2	2	1	1	1	1	0	0
Adsorption	1.00	0.46	0.29	370	0	0	0	0	0	0	0	0	0	0

6 Calculations for unit sizing

Moving bed biofilm reactor

Following assumptions and steps were taken to model the moving bed biofilm reactor.

BioWin's specific area = 500 m^2/m^3

BioWin's specific volume = 0.2

L:W ratio = 1:1

DO concentration = 5 mg/L

Mixing power for anoxic zone = 25 W/m^3

The media fill fraction and the recycle ratios in BioWin were adjusted manually until the desired effluent quality was achieved.

The reader is also referred to the following text for detailed explanation of the terms and the calculation methods: Tchobanoglous et al. (2013) (Refer Example 9-8, Page 1023), and Water Environment Federation (2010) (Refer Chapter 13)

Ultrafiltration/Nanofiltration

The area and power occupied by ultrafiltration and nanofiltration was directly derived from DuPont Water Treatment Solutions (2024) using the WAVE software.

Granular Activated Carbon

Service velocity = 0.15 m/min

Bed depth = 0.25 m

Contact time = 5 min

Backwash velocity = 0.35 m/min

Expansion = 0.35 x Bed depth

Freeboard = 0.3 m

Contact time < 30 minutes

Total height = Bed height + expansion + freeboard

Area = Operating velocity / service velocity

UV Disinfection

UV dose = "For reclaimed water systems, the recommended design UV doses for various effluents are 100 mJ/cm^2 for media filtration or equivalent effluent, 80 mJ/cm^2 for membrane filtration effluent, and 50 mJ/cm^2 for reverse osmosis effluent." Tchobanoglous et al. (2013). The reader is referred to Tchobanoglous et al. (2013) (Refer Example 12-15, Page 1420) for details on how to size a UV disinfection unit.

7 Uncertainty analysis

Co-treatment of greywater and blackwater

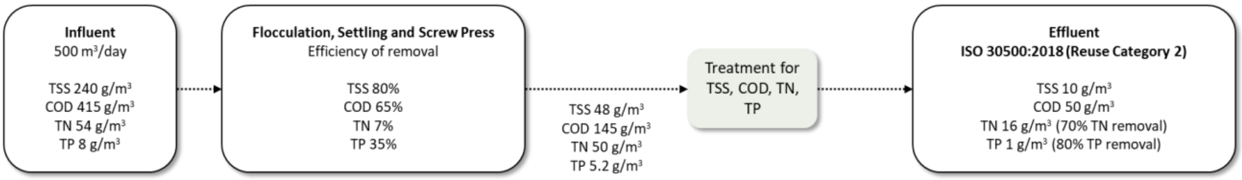


Figure 21: Schematic representing the input and output parameters for scenario co-treatment of greywater and blackwater of uncertainty analysis

100% urine separation

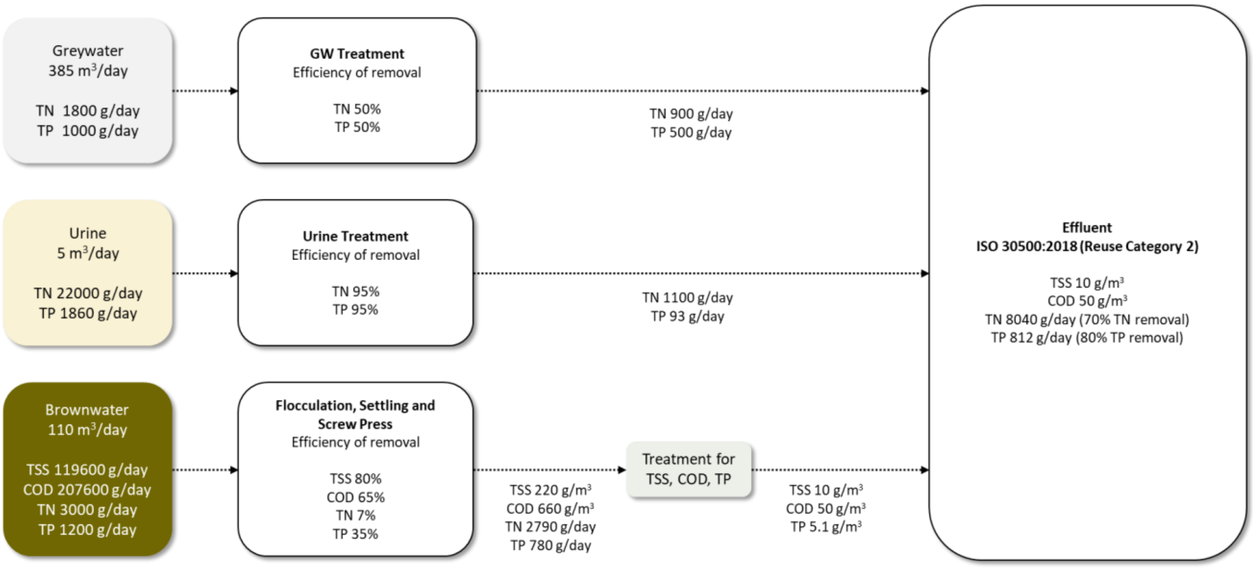


Figure 22: Schematic representing the input and output parameters for scenario 100% urine separation of uncertainty analysis

0% urine separation

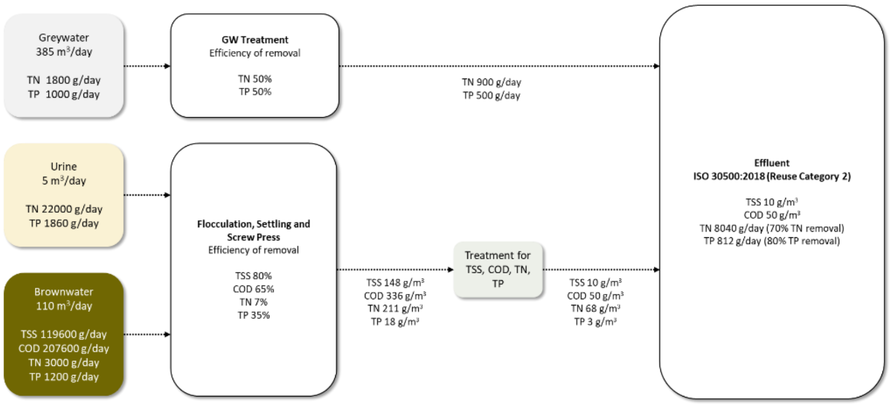


Figure 23: Schematic representing the input and output parameters for scenario 0% urine separation of uncertainty analysis

Blackwater supernatant treatment

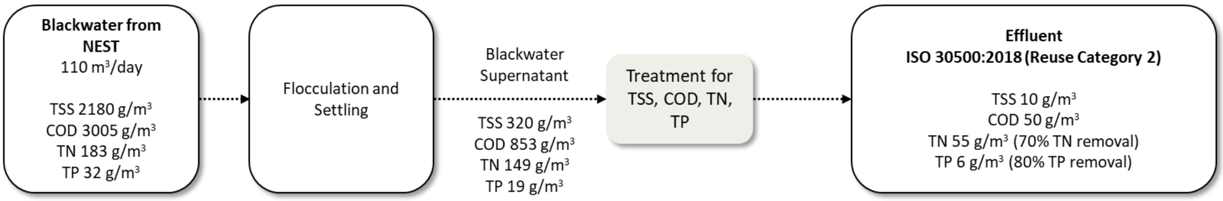


Figure 24: Schematic representing the input and output parameters for scenario blackwater supernatant treatment of uncertainty analysis

Worst efficiency of primary treatment

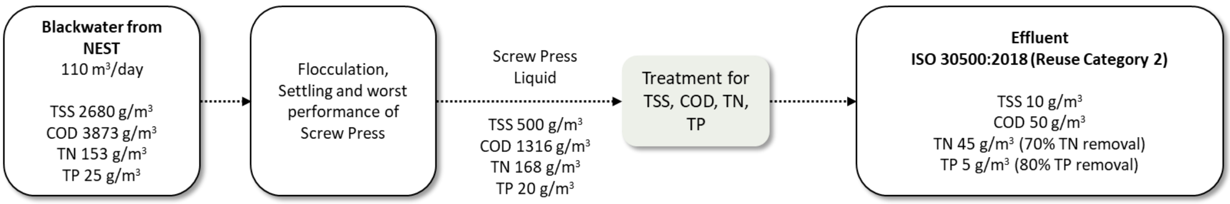


Figure 25: Schematic representing the input and output parameters for scenario worst efficiency of primary treatment of uncertainty analysis

Flow rates in other urban communities

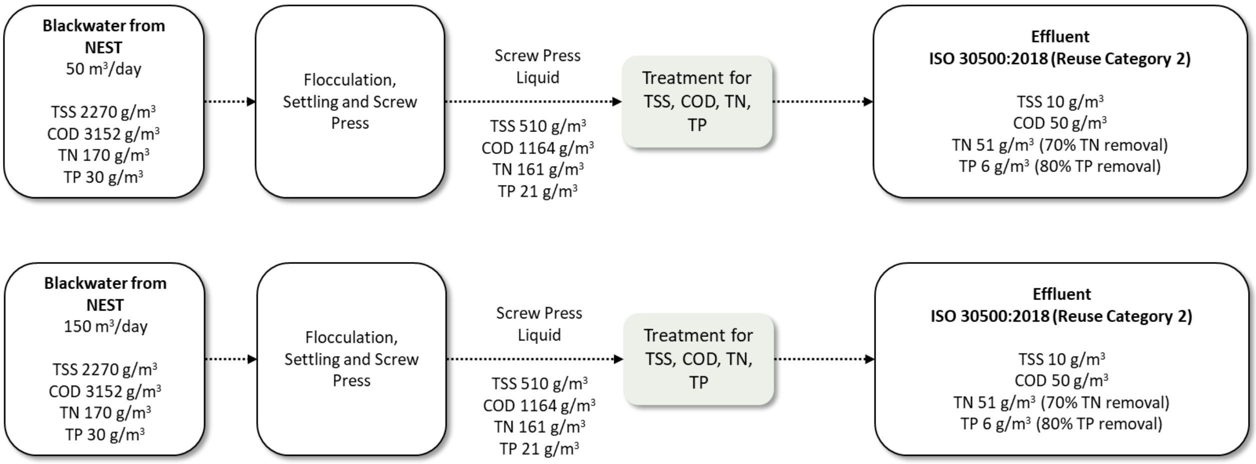


Figure 26: Schematic representing the input and output parameters for scenario variation in flow rates in other urban communities of uncertainty analysis

Reference data used for deriving the quality of blackwater, greywater, and urine

Table 18: Reference data used for deriving the quality of blackwater, greywater, and urine

g·p−1·d−1	Greywater			Urine			Feces			Toilet Paper		
	min	max	avg	min	max	avg	min	max	avg	min	max	avg
TSS	2	25	19	0	0	12	6	60	22	6.8	6.8	6.8
VSS	1.6	20	6.9	0	0	0	0	0	0	0	0	0
COD_t	7	102	51	5	24	13	2.6	63	31	8.8	8.8	8.8
$BOD_{5,\,t}$	1	63	19	1.8	10	5.80	4.3	20	12	0	0	0
TN	0.01	2.3	0.9	4	16	11	0.3	4.20	1.5	0	0	0
NH_3-N	0.11	1.3	0.32	0.32	0.88	0.55	0.01	0.59	0.3	0	0	0
NO_3-N	0.01	2.5	0.64	0	0	0	0	0	0	0	0	0
PO_4-P	0.02	0.41	0.14	0.76	1.9	0.88	0.29	0.76	0.57	0	0	0
TP	0.00	2.2	0.5	0.8	2.0	0.93	0.3	0.80	0.6	0	0	0

8 Dataset of emission factors

Table 19: Dataset of emission factors for calculation of carbon footprint.

Component	Emission Factor	Units	Data source
Brownwater treatment unit			
Primary + MBBR + Settler - CH_4	0.006	kg CH_4/kg COD removed	Average from Wang et al. (2022); X. Zhou et al. (2022)
Primary + MBBR + Settler - N_2O	0.017	kg N_2O/kg TN removed	Average from Wang et al. (2022); X. Zhou et al. (2022)
Aluminium sulphate production	0.71	kg CO_2-eq/kg	Ecoinvent (2024)
Polyacrylamide production	3.944	kgCO_2-eq/kg	Ecoinvent (2024)
Ultrafiltration production	2.54	kgCO_2-eq/unit	Ecoinvent (2024)
Granular activated carbon production	8.5185	kgCO_2-eq/kg	Ecoinvent (2024)
UV production	1.088	kgCO_2-eq/unit	Ecoinvent (2024)
Total energy consumption	2	kWh/m^3	From BioWin modelling
Greywater treatment unit			
Primary + MBBR + Settler - CH_4	0.006	kg CH_4/kg COD removed	Average from Wang et al. (2022); X. Zhou et al. (2022)
Primary + MBBR + Settler - N_2O	0.017	kg N_2O/kg TN removed	Average from Wang et al. (2022); X. Zhou et al. (2022)
Sodium hypochlorite production	2.55	kgCO_2-eq/kg	Ecoinvent (2024)
Ultrafiltration production	2.54	kgCO_2-eq/unit	Ecoinvent (2024)
Total energy consumption	6	kWh/m^3	Assumed
Urine treatment unit			
Collection tank + Nitrification – CH_4	0.09	kgCO_2-eq/kgTN-influent	Faust et al. (2022)
Intermediate storage – N_2O	0.8	%	Faust et al. (2022)
Nitrification	0.7	%	Faust et al. (2022)
Total energy consumption with distillation	119	kWh/m^3	Faust et al. (2022)
Total energy consumption without distillation	12	kWh/m^3	Faust et al. (2022)
Grid electricity production emission factors			
Burkina Faso	0.578	kgCO_2-eq/kWh	Tsukui et al. (2024a)
India	0.9714	kgCO_2-eq/kWh	Tsukui et al. (2024a)
South Africa	1.0262	kgCO_2-eq/kWh	Tsukui et al. (2024a)
People's Republic of China	0.5572	kgCO_2-eq/kWh	Tsukui et al. (2024a)
Switzerland	0.151	kgCO_2-eq/kWh	Romano (2019)
United States of America	0.39	kgCO_2-eq/kWh	U.S. Energy Information Administration (2024)

9 Dataset of flow rates observed in NEST

Table 20: Flow rates observed in NEST on 26 February 2024

Start time	End time	Start level	End level	Hours	Litres	Flow rate (L/hour)
08:49:00	09:46:15	5.20	41.00	0.95	35.80	38
09:47:46	10:09:56	10.1	45.7	0.37	35.60	96
10:11:33	10:30:33	9.7	44.7	0.32	35.00	111
10:32:22	10:57:40	9.5	40.2	0.42	30.70	73
10:58:59	11:06:48	10.5	44.1	0.13	33.60	258
11:08:18	11:14:22	9.7	46.9	0.10	37.20	368
11:15:50	12:51:12	10.5	40.6	1.59	30.10	19
12:52:33	13:41:40	10.3	44.3	0.82	34.00	42
13:43:26	13:59:26	9.9	41.2	0.27	31.30	117
14:00:45	15:05:58	10.1	41.4	1.09	31.30	29
15:08:05	15:50:20	9.9	40	0.70	30.10	43
15:52:05	17:09:24	9.9	40.4	1.29	30.50	24
17:10:49	18:32:44	9.7	42.4	1.37	32.70	24
18:34:27	20:00:33	9.3	43.6	1.44	34.30	24
20:02:22	22:26:29	10.3	40	2.40	29.70	12
22:27:59	23:17:04	10.1	40.2	0.82	30.10	37
23:18:43	23:59:59	10.1	34.9	0.69	24.80	36

Table 21: Flow rates observed in NEST on 27 February 2024

Start time	End time	Start level	End level	Hours	Litres	Flow rate (L/hour)
00:00:00	00:13:15	34.9	43.8	0.22	8.9	40
00:14:45	07:29:00	9.5	41.4	7.24	31.9	4
07:30:18	08:29:00	9.7	42.6	0.98	32.9	34
08:30:15	08:42:58	9.7	40.4	0.21	30.7	145
08:44:32	09:15:16	9.7	45.7	0.51	36	70
09:16:46	09:43:57	10.3	58.7	0.45	48.4	107
09:45:59	10:20:53	9.9	40.2	0.58	30.3	52
10:22:14	10:39:20	9.7	40.6	0.29	30.9	108

Table 22: Flow rates observed in NEST on 28 February 2024

Start time	End time	Start level	End level	Hours	Litres	Flow rate (L/hour)
10:56:04	11:27:22	13.1	40.4	0.52	27.3	52
11:28:34	12:35:47	9.7	42.4	1.12	32.7	29
12:37:20	13:00:24	10.1	41.2	0.38	31.1	81
13:01:50	13:15:26	10.1	46.5	0.23	36.4	161
13:17:11	13:29:18	10.3	44	0.20	33.7	167
13:31:01	13:51:26	9.5	40.2	0.34	30.7	90
13:52:32	15:28:41	9.7	45.5	1.60	35.8	22
15:30:09	16:10:49	10.1	40	0.68	29.9	44
16:11:58	17:05:15	9.7	41	0.89	31.3	35
17:06:25	17:39:30	9.1	40	0.55	30.9	56
17:41:16	18:57:42	9.5	40	1.27	30.5	24
18:58:57	21:31:57	9.7	42	2.55	32.3	13
21:33:13	23:59:59	9.5	40.2	2.45	30.7	13

Table 23: Flow rates observed in NEST on 29 February 2024

Start time	End time	Start level	End level	Hours	Litres	Flow rate (L/hour)
00:01:28	06:54:59	9.5	41.4	6.9	31.9	5
06:56:10	08:17:21	9.3	40	1.4	30.7	23
08:18:37	09:06:22	9.1	40.2	0.8	31.1	39
09:07:53	09:48:12	10.1	43.4	0.7	33.3	50
09:50:01	10:18:07	9.7	43.6	0.5	33.9	72
10:19:35	10:46:00	9.9	47.7	0.4	37.8	86
10:48:20	11:09:38	9.3	42.4	0.4	33.1	93
11:11:20	11:31:28	9.3	45.1	0.3	35.8	107
11:33:04	11:51:40	9.5	45.7	0.3	36.2	117
11:53:16	12:38:47	10.1	40.8	0.8	30.7	40
12:40:00	13:03:49	8.7	43.2	0.4	34.5	87
13:05:39	13:45:28	9.3	42.4	0.7	33.1	50
13:46:55	14:35:15	9.1	55.2	0.8	46.1	57
14:37:22	15:31:05	9.9	46.7	0.9	36.8	41
15:32:36	16:29:39	9.7	40.2	1.0	30.5	32
16:30:51	17:35:23	9.9	41.8	1.1	31.9	30
17:36:36	18:19:30	9.1	44	0.7	34.9	49
18:20:59	22:09:21	10.1	40.2	3.8	30.1	8
22:10:32	23:37:46	10.3	41.8	1.5	31.5	22

Table 24: Flow rates observed in NEST on 1 March, 2024

Start time	End time	Start level	End level	Hours	Litres	Flow rate (L/hour)
00:00:00	06:58:58	16.6	43.6	6.98	27	4
07:00:17	09:00:18	9.7	43.2	2.00	33.5	17
09:01:50	09:30:58	9.9	29.2	0.49	19.3	40
12:30:00	12:41:11	14.4	41.6	0.19	27.2	146
12:42:37	13:04:29	9.7	42.2	0.36	32.5	89
13:06:09	14:30:00	10.7	42.4	1.40	31.7	23
14:31:28	15:15:36	9.9	40	0.74	30.1	41
15:17:28	16:08:50	9.5	40.8	0.86	31.3	37
16:10:10	16:48:14	9.9	40	0.63	30.1	47
16:49:37	17:21:27	9.7	47.5	0.53	37.8	71
17:23:09	17:29:53	9.7	13.1	0.11	3.4	30

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