Assessing the Feasibility of Decentralized Wastewater Treatment Systems for Rural Communities in Developing Countries

MASTER THESIS

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Usage of artificial intelligence

In the preparation of this work, the GPT tool was used, exclusively for translation and spelling check purposes. An examination of the proposed results has been conducted, and the responsibility for their accuracy rests solely with the student.

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Abstract

In 2010, the United Nations officially recognized the right to water as a human right and since 2015, access to clean water and sanitation has been included in the UN Sustainable Development Goals (SDGs). In this context, effective management and treatment of wastewater are crucial, especially in developing countries. A promising approach to cost- and energy-efficient wastewater treatment is decentralized treatment systems.

This thesis assesses the feasibility of decentralized wastewater treatment systems for rural areas in developing countries through a techno-economic analysis. The study focuses on the rural area of the Northern Gondar Region in Ethiopia as a case study. In this region, there is no centralized wastewater treatment facility and no reliable connection to an electricity grid. In this context natural treatment systems emerge as the most promising option.

Within this subgroup of natural treatment systems, constructed wetlands prove to be a more promising method for effective wastewater treatment compared to waste stabilization ponds. The main reason for this is the significantly smaller land area required by this system. At the same time, CW systems deliver excellent results in removing key pollutants such as biological oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS). Although the implementation of waste stabilization ponds generally incurs lower costs, the higher acceptance of the CW system among the population in an agriculturally driven region is attributed to its space-saving nature. This system requires less farmland, thereby generating lower opportunity costs.

The feasibility of both systems is confirmed, but it is also determined that such a wastewater project in the rural context of developing countries is only possible through the active involvement of the community in the maintenance of the facility. Ensuring the long-term functionality of the systems must, therefore, focus on educating and training the local population. The approach taken in this work can serve as a model for other regions, as specific local conditions, such as the lack of connection to an electricity grid, are decisive factors in the findings.

Contents

1 Introduction

A clean water supply and proper water and wastewater management have significantly contributed to the advancement of humanity[1]. The task of this master's thesis is to examine the feasibility of decentralized wastewater systems in an exemplary rural area in a developing country and to carry out a Techno Economical Analysis (TEA) in order to identify the most suitable option.

1.1 Problem Statement: Lack of Efficient Wastewater Systems in Rural Areas

According to the World Health Organization (WHO), 1.5 million people still every year from diarrhoeal diseases[2] that are closely linked to inadequate wastewater management. This figure is particularly alarming in rural areas of developing countries, where access to sanitation services is the exception rather than the rule[3]. It is estimated that more than 2.6 billion people are still without adequate sanitation, of which 70% live in rural areas. For rural populations in many developing countries, primitive cesspools remain the predominant method of disposing of domestic wastewater. In these regions, decentralized wastewater treatment represents a promising alternative to the existing and often inadequate disposal methods.[4]

The various methods of wastewater treatment must be adapted to the specific social, ecological and economic conditions of each region[5]. In addition, decentralized wastewater treatment plants are known for their resource efficiency and cost-effectiveness[6]. The main challenge is to accurately assess and predict the potential and viability of decentralized wastewater treatment systems. Several key issues need to be considered, including technical feasibility, economic viability, environmental impact, social acceptance, knowledge transfer and capacity building. The main objective of this study is to develop a resource-efficient approach to wastewater treatment that ideally requires little or no electricity for operation, uses local materials, is user-friendly and is based on biological processes.[7]

1.2 Overall Objective: Analyzing the Feasibility of Decentralized Wastewater Solutions

The main objectives of this project are to investigate common wastewater treatment methods and explore their application in rural areas. To achieve these primary outputs, the following steps must be accomplished:

- Comparison of the most prevalent wastewater treatment methods and subsequently identifying the most promising approaches for the considered region
- Optimization and adaptation of the selected methods to suit the local conditions
- Evaluation of the technical feasibility and financial estimation of the proposed methods
- Long-term projections concerning the the functionality of the decentralized wastewater system

1.3 Research Hypothesis: Decentralized Systems as Viable Solutions for Rural Communities

In rural areas of developing countries, there is a clear lack of functional and sustainable wastewater systems. In view of the impossibility or economic infeasibility of a centralized wastewater infrastructure in these regions, the use of decentralized wastewater treatment systems is a rational alternative. However, a variety of solutions for decentralized wastewater supply exist. The optimal solution must be identified, evaluated and provided with the overall objective that it is ultimately beneficial for all affected people in the region in both technical and economic terms.

1.4 Research Questions on the Feasibility of Decentralized Systems

1. What are the key technical components and considerations in the planning and implementation of decentralized wastewater treatment systems?
2. What economic factors influence the feasibility of decentralized wastewater treatment systems in rural communities in developing countries?
3. How do decentralized wastewater treatment systems compare in terms of effectiveness, efficiency and affordability in rural communities?

2 Sanitation and Wastewater Treatment in Developing Countries

Almost 40 % [8] of the world's population still suffers from inadequate sanitation and only about 4 % [9] of the population of low-income countries have a privilege of being connected to a centralized sewer system. The result is that, many people, especially in rural areas, are forced into open defecation[8]. If there are sanitary facilities in the form of latrines, which actually collect human excrement in the form of Septic Tank (ST) or cesspits, the material, size and maintenance are often reduced in order to save costs[10]. The untreated and uncontrolled release of more then 90 % [11] of sewage waste into rivers and water bodies, marks one of the most severe problems for wastewater treatment in developing countries. This results in permanent pollution of freshwater sources. Especially in developing countries, awareness of this problem is still relatively low[12], which increases the associated health risks when reusing wastewater. An intact ecosystem is particularly essential in developing countries, as these countries are usually heavily agricultural. Therefore, the United Nations adopted the 17 SDG (SDG) (see Figure 1) to address global environmental, economic and social challenges.[13]

One approach to solving the problem of wastewater technology that developing countries are currently dealing with (SDG 6), is decentralized wastewater treatment[14].

Figure 1: UN Sustainable Development Goals [15] (used with permission)

2.1 Wastewater Treatment Ethiopia

The focus of the feasibility assessment for decentralized wastewater systems will be on the developing country Ethiopia[16]. Most household wastewater in this country is discharged untreated into nearby water bodies or into nature, causing serious problems for the environment and human health.[17]

There is no sewerage system outside the capital Addis Ababa, where also only around 12 % [18] of the population is connected to. The wastewater problem is particularly evident in the collection and disposal of wastewater. In a representative survey, only 45 % [19] of the country's inhabitants state out, that when a toilet facility is full they have this facility emptied using vacuum trucks. 23 % [19] simply decide to build a new facility, while the rest either do not want to express an opinion or do not collect excreta due to open defecation. Leakages and overflows lead to pollution and contamination of the environment and groundwater. Almost none of the regions in Ethiopia have a properly designed wastewater disposal point. Wastewater is therefore usually simply disposed of next to solid waste landfills. Pits are repeatedly dug and filled with wastewater and as soon as these are full, new ones are simply dug.[19]

The uncontrolled discharge of wastewater is particularly widespread in rural areas, where there are even fewer control bodies and awareness of the problem[20]. Decentralized on-site treatment of wastewater in Ethiopia therefore appears to be the more reasonable option in many aspects. This involves the treatment of domestic wastewater and includes black water and grey water.[21]

2.1.1 Spotlight Amhara Region

One of the twelve regions in Ethiopia is the Amhara region[22], which is clearly marked with the red circle in Figure 2, as the assessment on the feasibility of decentralized wastewater systems for rural areas in developing countries refers to this representative region.

Figure 2: Location of Amhara Region within Ethiopia's administrative regions [23] (adapted)

The Amhara region in northwestern Ethiopia is one of the most populous districts in the entire country. About 88 % of the population in the Amhara region lives in rural areas.[24]

Within the Amhara region, only 1.7 % [25] of the population has access to improved sanitation facilities, while 32 % [25] of the population uses the unhygienic practice of open defecation. The region is heavily dependent on agriculture, especially subsistence farming. Clean water and groundwater is therefore essential for the inhabitants of this region.[26]

The Amhara region is home to Lake Tana, the largest lake in Ethiopia[27] and the Magech River. Uncontrolled discharge of wastewater has led to a increase in pollution in these waterbodies, which has already affects on the surrounding agriculture[28]. The degree of pollution of the lake and the classification of the water quality as unsatisfactory are examples of the lack of awareness among the population about how to deal with waste water[29]. Therefore, diarrheal diseases are widespread in households[30] and in general, the environment in this region can be described as unsanitary. The rural nature of the Amhara region makes it an ideal study area for the feasibility study of decentralized wastewater systems. Since the Amhara region is one of the largest in Ethiopia[24], the representative study area is centered on the North Gondar region. In the northern Gondar zone, the altitude is between 1780-2700 meter above sea level[31], with an average temperature of 20 °C[32]. To be more specific, the region respective research region marks the area between the town of Gonder and the northern part of Lake Tana (Figure 3).

Figure 3: Research Area Northern Gondar District, Ethiopia (own illustration)

3 Decentralized Wastewater Treatment

Decentralized wastewater systems enable a type of decoupled treatment of wastewater. Although they are typically designed for individual households or businesses, decentralized wastewater systems can also serve several households or different wastewater sources in a cluster. The use of decentralized wastewater systems is far more widespread in emerging and developing countries than in industrialized countries.[33]

According to available data, only 10-20 %[34] of the wastewater produced in the Sub-Saharan region is treated safely on average. Often fresh water and groundwater resources can no longer meet the increasing demand[35]. It is therefore necessary to resort to a resource-saving and low-energy type of wastewater treatment. Due to the lack of water infrastructure, decentralized wastewater treatment remains the only way to ensure safe water treatment.[36]

3.1 Decentralized Wastewater Treatment vs. Centralized Wastewater Treatment

Centralized wastewater treatment differs from decentralized wastewater treatment plants in many aspects. Figure 4 shows a simple visualization of how the different levels of wastewater treatment can be classified.

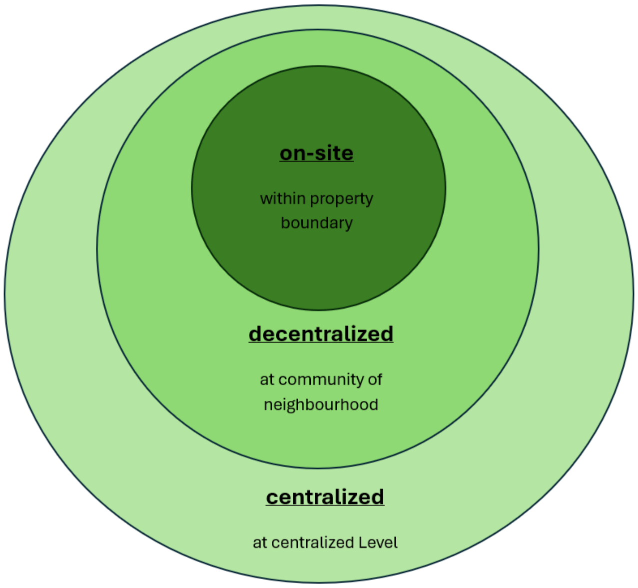

Figure 4: Representation of the Three Organizational Levels of Wastewater Treatment [37] (redrawn)

With centralized wastewater treatment, there is a wastewater treatment plant outside the inhabited area, which supplies a large part of the population. The centralized approach is therefore particularly suitable for densely populated areas. Decentralized wastewater treatment, on the other hand, takes place directly at the source of the wastewater. Therefore the differences between the two approaches start right from the collection process, as shown in Figure 5. While in centralized wastewater management the wastewater is fed into a central sewer system via inlets (see "a." in Figure 5), in decentralized systems the wastewater is often collected by discharging it into a ST or simply through a pit well (see "b." and "c." in Figure 5).[38]

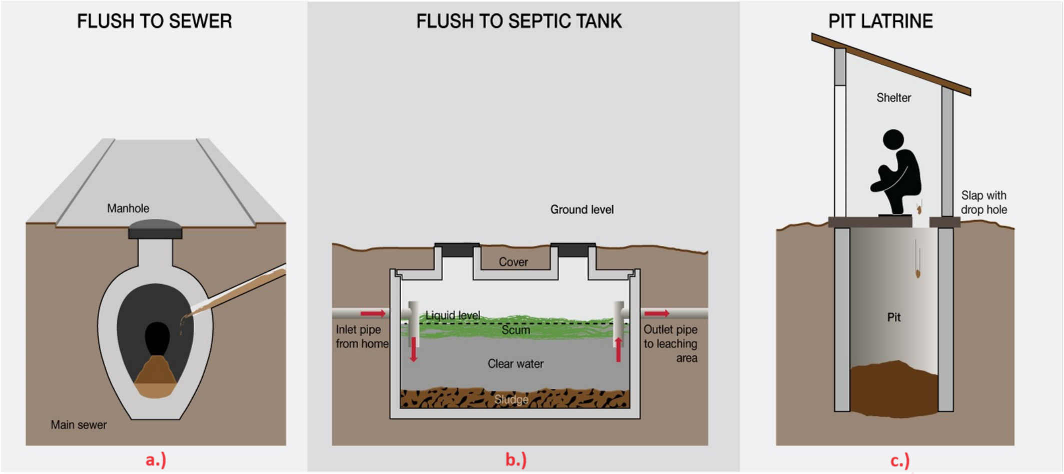

Figure 5: Centralized and Decentralized Wastewater Collection Methods [39] (adapted)

The construction of a centralized wastewater system therefore involves considerably more effort and significantly higher initial costs[40]. Therefore the installation of decentralized systems, especially in remote or rural areas, often makes much more economic sense[40]. Furthermore, centralized wastewater management requires significant resources due to its higher energy requirements and associated operating costs, as well as greater expertise and training of those responsible. Although the centralized system, due to its size, is generally less adaptable and cannot be easily adjusted to changing conditions, but it offers the advantage of highly efficient treatment. Small scaled decentralized systems, on the other hand, allow for easier piloting of new technologies, but newly developed methods for on-site treatment often appear less reliable and challenges in handling sewage sludge are frequently observed.[41]

The high energy dependency of centralized wastewater systems, due to the often long pumping distances, has an impact on the ecological footprint. In addition, a functioning wastewater infrastructure and the transportation of wastewater require large quantities of water[42]. In terms of maintenance, it is crucial to carry out regular maintenance work on all systems. However, employees in large centralized wastewater systems are usually much better trained and educated than those responsible for decentralized wastewater systems. Therefore, the use of decentralized wastewater treatment often fails due to insufficient knowledge of proper maintenance, servicing and operation.[43]

Another reason for the failure of introducing decentralized wastewater systems is their location close to the source of the wastewater and the associated possibility of unpleasant odors and animals such as rats or mosquitoes, depending on the area in which the system is used.[44]

3.2 Most Common Decentralized Treatment and Disposal Methods

There are a large number of decentralized approaches to wastewater treatment, with each method having specific advantages and disadvantages for its respective application scenario. The following categorization is used to systematically classify[45] these methods:

1. Natural Treatment Systems (NTS)
2. Aerobic Systems
3. Anaerobic Systems
4. Hybrid Systems

In Appendix A, these methods are explained more into detail.

4 Methodology and Definition of the Analysis Parameters

In assessing the feasibility of implementing a decentralized wastewater treatment system in the specified Ethiopian region, a Techno-Economic Analysis will be conducted. As relying solely on technical assessments overlooks the unique challenges of securing funding for such non-monetarily profitable technologies, especially in developing countries.[46]

4.1 Methodology

For the assessment of the feasibility of decentralized wastewater treatment systems, a combination of methods are employed. The literature review on the various groups of decentralized wastewater systems and the local Ethiopian conditions is the foundation for the subsequent case study analysis. This case study analysis focuses on the treatment efficiency of the systems based on established pollution parameters, which will be referenced in chapter 4.2. This comparison function as technical pre-selection of the available methods.

After determining the suitable methods for wastewater treatment, a TEA compares the relevant methods. This analysis is based on a weighting of analytical parameters, derived from an expert survey (see Appendix C). In the TEA, a theoretical system design will be defined for each method and the systems will then be evaluated in the sections "Effluent Characteristics," "Technical Parameters," and "Economic Parameters" based on their weighted performance in the respective parameters of these sections. Additionally, the results are supplemented by finding from an expert interview (see Appendix D).

In the economic analysis, a detailed cost structure of the respective systems are also calculated and the main cost drivers of each system are identified through sensitivity analysis and Monte Carlo simulation. Furthermore, the calculated costs are projected within the overall cost structure of each system to validate the economic comparability of the systems. Considering the socio-economic aspects, a final recommendation for a suitable system is achieved.

4.2 Definition of Parameters

Conducting a Techno-Economic Analysis necessitates both technical and economic parameters. The analysis parameters are divided into three sections, namely "Effluent Characteristics," "Technical Parameters," and "Economical Parameters." A detailed definition of each parameter can be found in Appendix B.[47]

4.2.1 Section A: Wastewater Effluent Characteristics

Firstly, the analysis focus on the effectiveness of water purification based on wastewater effluent characteristics[48]. This implies an assessment of the degree of contamination present in the wastewater following the specific type of water treatment. The corresponding parameters here are:

- Biological Oxygen Demand (BOD)
- Chemical Oxygen Demand (COD)

- Total Suspended Solids (TSS)
- Fecal Coliforms (FC)
- Phosphorus/Total Phosphorus (TP)
- Ammonia/Total Nitrogen (TN)

4.2.2 Section B: Technical Parameters

In addition to effluent characteristics, various technical parameters play an essential role in the analysis of different decentralized wastewater treatment systems[49]. The technical parameters here are:

- Scalability
- Energy Requirement
- Hydraulic Retention Time (HRT)/ Sludge Retention Time (SRT)
- Sludge Management
- Maintenance needs
- Area

4.2.3 Section C: Economical Parameters

The implementation of a new wastewater system is inevitably associated with financial expenditures. Especially for developing countries, these investments pose a significant factor[50]. The economical parameters are:

- Initial Capital Cost
- Operation and Maintenance (O&M)
- Life Cycle Cost (LCC)

5 Case Studies and Technical Preselesction

The advantage of a case study analysis lies in the ability to utilize primary data from decentralized wastewater treatment systems that have been deployed under similar conditions. Overall objective is to conduct a broad analysis of the different technologies.[51]

This technical preselection emphasizes applications in the developing country of Ethiopia. Therefore, the legal limits for pollutant concentrations in wastewater after treatment (see Table 1) of the East African country serve as the reference for evaluating the case study systems.

Table 1: Legal Limits Wastewater Effluent Concentrations After Treatment in Ethiopia [52][53]

BOD (mg/L)	COD (mg/L)	TSS (mg/L)	FC (MPN/100ml)	TP (mg/L)	TN (mg/L)
50	**250**	**50**	**1000**	**2**	**40**

To generalize further metrics, the population size to be served in the rural area is set at 10-200 people. The Average Wastewater Production (AWP) varies depending on the region and social status. For simplicity, the average production per inhabitant of Sub-Saharan Africa is used, which is 11.0 m^3/year.[54]

$$Average\ Wastewater\ Inflow = \frac{AWP\ per\ person}{365\,\mathrm{days}} \cdot number\ of\ people \tag{1}$$

$$\frac{11.0\,\mathrm{m}^3/\mathrm{year}}{365\,\mathrm{days}} \cdot 200 = 6\,\mathrm{m}^3 \tag{2}$$

For the considered region in the Northern Amhara Region and thus for the design of the decentralized wastewater treatment plant, an average wastewater inflow of approximately 6 m^3/day 2 is expected. For all the case studies considered, the treated wastewater is always domestic wastewater. This includes wastewater originating from human activities, such as blackwater from restroom use and greywater from laundry, kitchen and bathroom activities.[55]

5.1 Case Study Analysis: Natural Treatment Systems

A promising method for decentralized wastewater treatment that is both energy-efficient and low-maintenance is marked by natural wastewater treatment systems. These systems are considered particularly practical in economic terms and thus especially optimal for countries in the Global South.[56]

Waste Stabilization Ponds

In the area of NTS, Waste Stabilization Pond (WSP) offer a promising solution for developing countries[57] . The benefits of this simple and straightforward form of wastewater treatment are primarily its cost-effectiveness, low energy consumption and minimal maintenance needs[58]. However, these advantages are accompanied by drawbacks, such as the relatively large land area required for its implementation[58]. Generally, there are three main types of ponds to distinguish: anaerobic, facultative and maturation ponds. Any other form of WSP is a modification of these main types. These ponds can be used either independently or in series (see Figure 6).[59]

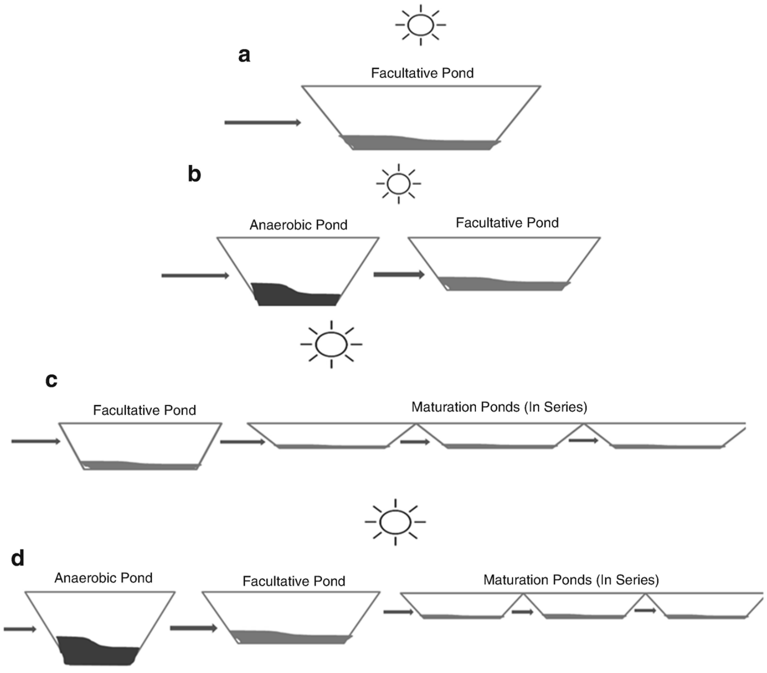

Figure 6: Most Commonly Used WSP System Structures [59] (used with permission)

Figure 6 "a" shows a facultative pond, which requires a large land area and sunlight for algae to assist in wastewater treatment. In the upper aerobic zone, algae stabilize organic matter, while in the lower anaerobic zone, it settles and degrades in the sludge[60]. Facultative ponds follow the pretreatment by anaerobic ponds (Figure 6 "b"), which handle a high organic load and remove BOD under anaerobic conditions[61]. Figure 6 "c", illustrates maturation ponds, which remove pathogens through solar disinfection, following the removal of BOD, TSS and nutrients by previous ponds. Solar radiation plays a crucial role in this pond type. The shallow design allows for strong photosynthesis by algae present in the pond and solar disinfection, through ultraviolet radiation, effectively eliminates pathogens.[62] Scenario "d" combines all pond types for optimal treatment but increases costs and land use[63].

WSP perform best in warm climates with high levels of sunlight[64]. Like in the Northern Gondar region, where temperatures typically never drop below 10 °C and the area has an average annual temperature of 20 °C. Additionally, the area enjoys over 2,640 hours of sunshine per year.[32]

In Ethiopia, specifically in the southwest near the city of Jimma, WSPs have already been tested. The climatic conditions there are almost identical to those in the Northern Gondar region, with slightly lower average temperatures (19.7 °C)[65] and fewer sunshine hours (2,350 h)[65]. The facility in Jimma is constructed as depicted in Figure 6 "d", featuring two parallel anaerobic ponds followed by a facultative pond, which in turn is followed by four maturation ponds, before the water is finally discharged into a river. This system handles a raw wastewater flow of 2250 m^3/day, serving a larger area.[66].

Table 2: Wastewater Effluent Pollution Concentration Case Study WSP Jimma, Ethiopia [66]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	117.0	75.3
COD (mg/L)	457.5	56.5
TSS (mg/L)	220.5	65.8
TP (mg/L)	4.8	69.2
TN (mg/L)	17.4	79.0
FC (MPN/100ml)	810	94.3

Table 2 indicates that the facility meets Ethiopian guidelines only for the removal of TN and FC (see Table 1). Implementing pretreatment can reduce the organic load in raw wastewater, further enhancing treatment efficiency.[67]

In the following case study, the effectiveness of a decentralized wastewater treatment system in South Australia was tested. The climate data of Kingston on Murray settlement in Australia, with an annual average temperature of 25 °C [68] and annual sunshine hours of 3,130 hours[68]. The system used there is a High Rate Algal Pond (HRAP), which is essentially a modification of the maturation pond. This pond is typically even shallower, with a depth of 0.2 m to 0.7 m[69]. The system consists of a ST for pretreatment, followed by a facultative pond for further treatment. Finally, the wastewater is treated in a ´the HRAP before being reused in agriculture. The wastewater inflow is 12 m^3/day[70].

Table 3: Wastewater Effluent Pollution Concentration Case Study WSP Kingston on Murray, Australia [70]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	8.0	96.0
TSS (mg/L)	57.0	43.6
TP (mg/L)	7.4	40.8
TN (mg/L)	1.1	95.4
FC (MPN/100ml)	12	99.9

In the Table 3, it becomes clear that pretreatment through STs leads to BOD, ammonia and FC levels meeting Ethiopian guidelines, with TSS also nearly reaching acceptable levels (see Table 1)[70]. There are no specific data available for COD; however, given the significant removal efficiency of BOD and the correlation between BOD and COD[71], it is expected that results will comply with the guidelines.

A system similar to the one in Figure 6 "c" can be found in the the village Vamvakofyto in northeastern Greece, but with only two maturation ponds[72]. The average annual temperature there is around 18 °C [73], with an average of 2,303 hours of sunshine per year[73]. The daily wastewater inflow amounts to 120 m^3[72].

Table 4: Wastewater Effluent Pollution Concentration Case Study WSP Vamvakofyto, Greece [72]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	68.08	64.95
COD (mg/L)	78.57	69.89
TSS (mg/L)	23.04	62.01
TP (mg/L)	3.5	44.83
TN (mg/L)	2.95	88.13

The results show that the Ethiopian limits for the removal of TP and BOD could not be met (see Table 1.

In the city of Mzuzu in the African country of Malawi the average annual temperature is 17.7 °C [74] and the annual sunshine hours amount to 2,586 hours[74].

The system, as shown in Figure 6 "c", consists of a facultative pond followed by three maturation ponds[75] before the effluent is discharged into a nearby river. The wastewater inflow is 42 m^3/day[75].

Table 5: Wastewater Effluent Pollution Concentration Case Study WSP Mzuzu, Malawi [75]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	4.5	95.3
COD (mg/L)	51.0	78.7
TSS (mg/L)	18.0	63.7
TP (mg/L)	0.11	92.2
TN (mg/L)	0.01	48.0

Unfortunately, there is no data available for the FC.[75] However, the degradation of FC in WSP is directly correlated with temperature, with higher temperatures leading to higher removal efficiency.[76] In the region under consideration, the average temperature is 20 °C [32], which typically indicates a removal efficiency of FC in the range of over 90 %[76].

Constructed Wetlands

The energy and cost efficiency of NTS is also evident in the Constructed Wetland (CW) systems. The undisputed advantage of these systems is that they can operate entirely without energy, as long as no pumping is required[77]. Naturally, these treatment systems also have disadvantages, like the need for sufficient and affordable land[78]. The plants growing in the wetlands extract nutrients from the water. Microorganisms accumulating in the root zone of these plants then degrade pollutants[79]. CW systems generally operate under aerobic and anaerobic conditions due to the aeration provided by plant roots and oxygen diffusion from the surface[80]. However, anaerobic conditions occur in deeper zones of the CW. Both aerobic and anaerobic bacteria contribute to further reducing pollutant levels in the water[81]. Additionally, contaminants are removed through sedimentation, adsorption and filtration processes[82]. The efficiency of CWs correlates closely with the choice and management of appropriate filter media or substrates[83].

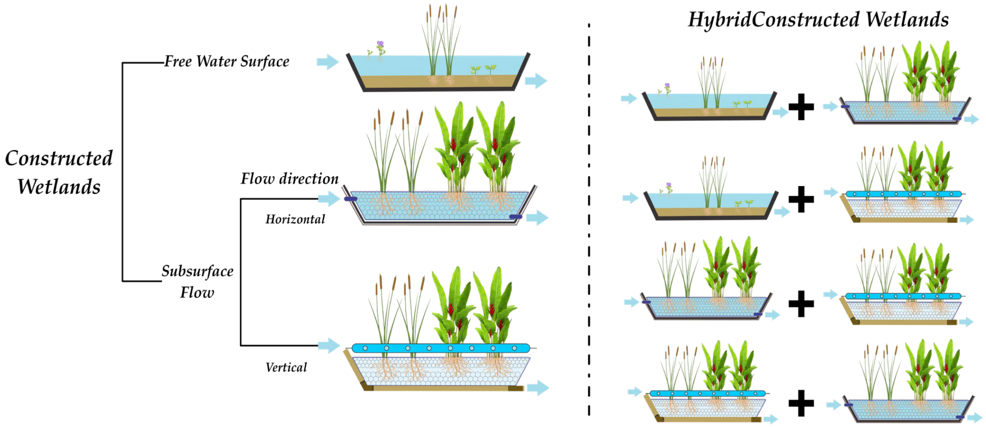

Figure 7: Most Commonly Used CW System Structures [84] (used with permission)

There are various types of CW systems. For simplicity, the focus is on the three main types, which are shown in the Figure 7. These are the so-called Free Water Surface (FWS) systems, Subsurface Flow (SSF) systems and Hybrid systems[85]. FWS systems most closely resemble naturally occurring wetlands. However, they require the largest land area and there is a risk of odor issues. In these systems, the wastewater flows over the surface of a shallow, plant-covered area.[86] SSF systems allow the wastewater to flow through a bed filled with materials like sand or gravel, in which plant roots grow. There are two types of flow in these systems: horizontal flow and vertical flow.[87] As the name suggests, in Horizontal Flow-Constructed Wetland (HF-CW), the wastewater flows horizontally through the gravel and sand-filled basin, where the selected plant type is located[88]. For the Vertical Flow-Constructed Wetland (VF-CW), the wastewater is applied from above onto the surface of the gravel and sand-filled basin through a mechanical dosing system. The advantage is that this setup requires even less land area and minimizes the potential for odor issues. However, the installation is significantly more complex and requires energy input.[89] Hybrid systems can combine the advantages of individual systems in various configurations[85].

In the village of Kothapally in India, the average temperature there is approximately 27 °C [90]. The wastewater inflow is 20 m^3/day. A HF-CW was used with sand and gravel as the filter media.[91]

Table 6: Wastewater Effluent Pollution Concentration Case Study CW Kothapally, India [91]

Parameter	Effluent Concentration	Removal Efficiency (%)
COD (mg/L)	92.3	61.5
TSS (mg/L)	7.2	86.2
TP (mg/L)	0.32	54.3
TN (mg/L)	15.59	61.08
FC (MPN/100ml)	124	92.7

Near the city of Ocotlán in Mexico, investigations were conducted for treating 0.1 m^3/day of domestic wastewater from a settlement. To treat wastewater, a VF-CW is used.[92] The average temperature in Ocotlán is 20 °C[93], with approximately 2,670 hours of sunshine annually[93]. The climatic conditions are nearly identical to those in the Northern Gondar Region in Ethiopia[32].

Table 7: Wastewater Effluent Pollution Concentration Case Study CW Ocotlán, Mexico [92]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	21.8	80.4
COD (mg/L)	56.4	77.2
TSS (mg/L)	22.4	53.2
TP (mg/L)	3.9	49.5
TN (mg/L)	14.8	48.1
FC (MPN/100ml)	68	97.0

In Egypt, in the eastern part of the Sharquiya Governorate, the average temperature is 22 °C[94] and the annual sunshine duration is 2,810 hours[94]. A notable aspect is the combination of a ST before of the HF-CW. This decentralized wastewater system has measured a flow of 10 m^3/day.[95]

Table 8: Wastewater Effluent Pollution Concentration Case Study CW Sharquiya Governorate, Egypt [95]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	36.0	79.0
COD (mg/L)	74.0	78.0
TSS (mg/L)	11.0	80.0
TN (mg/L)	15.3	80.0
FC (MPN/100ml)	300	99.9

A similar case in Tirana, Albania, shows a comparable pattern. However, the Albanian capital has a lower average temperature of 15 °C and receives fewer sunshine hours annually, with approximately 2,550 hours[96], compared to the Northern Gondar Region[32]. The treatment plant consists of a system with a settling tank, an HF-CW and a VF-CW and, which handles a flow of 16.8 m^3/day[97].

Table 9: Wastewater Effluent Pollution Concentration Case Study CW Tirana, Albania [97]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	5.0	98.3
COD (mg/L)	30.0	95.0
TSS (mg/L)	2.0	99.5
TP (mg/L)	6.0	40.0

The effluent characteristics of the decentralized wastewater treatment plant, which consists of a system with a settling tank, an HF-CW and a VF-CW and handles a flow of 16.8 m^3/day.[97]

5.2 Case Study Analysis: Aerobic Treatment Systems

The selection of case studies on the use of aerobic decentralized wastewater systems in developing countries is not very diverse. This is primarily due to the high costs associated with the implementation and operation of such systems.[98]

In Holt, Michigan, there is an aerobic decentralized wastewater treatment system in operation. Although the average annual temperature there is around 14 °C [99] , this implies that generally better results can be expected if the system is used in a warmer area[32].

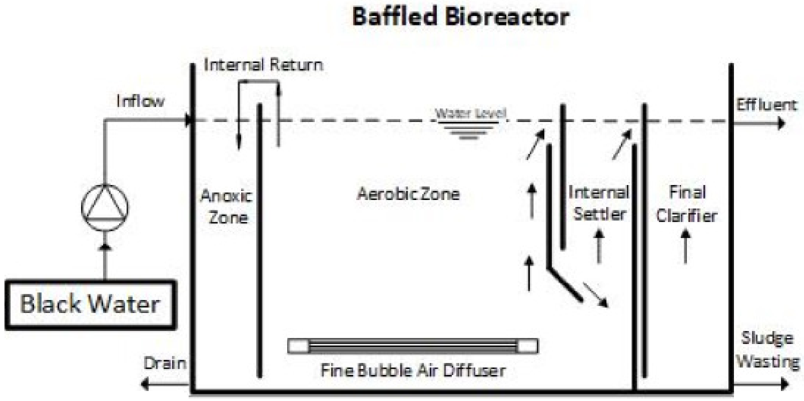

Figure 8: ABB Strcture and Wastewater Flow Direction [100] (adapted)

The system setup consists of an Aerobic Baffled Bioreactor (ABB). It functions by allowing blackwater to enter the reactor through the influent. The wastewater is supplied with oxygen via an air diffuser, which is necessary for the microorganisms that degrade organic matter, TN and TP. The baffles ensure continuous mixing and aeration, which enhances the effluent quality.[101]

Table 10: Wastewater Effluent Pollution Concentration Case Study ABB Holt, Michigan [100]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	74.6	95.1
COD (mg/L)	171.1	93.9
TSS (mg/L)	32.7	97.2
TP (mg/L)	3.9	96.05
TN (mg/L)	1.2	94.32
FC (MPN/100ml)	159	99.9

In this case study, 4.5 m^3/day[100] of highly contaminated wastewater was treated in the system, Unfortunately the effluent quality for BOD and TP did not meet Ethiopian standards (see Table 1). However, the aerobic baffled showed highly effective, as the efficiency for all parameters is above 94 %.[100]

In a Biological Compact Unit (BCU) (see Figure 9), marking the next aerobic treatment method, the wastewater is directed into the anaerobic compartment for a pretreatment process where organic matter is primarily converted into biogas. Subsequently, aerobic biological treatment takes place. Plastic pipes serve as the packing material, providing the contact surface for bacteria to degrade the organic matter.[102]

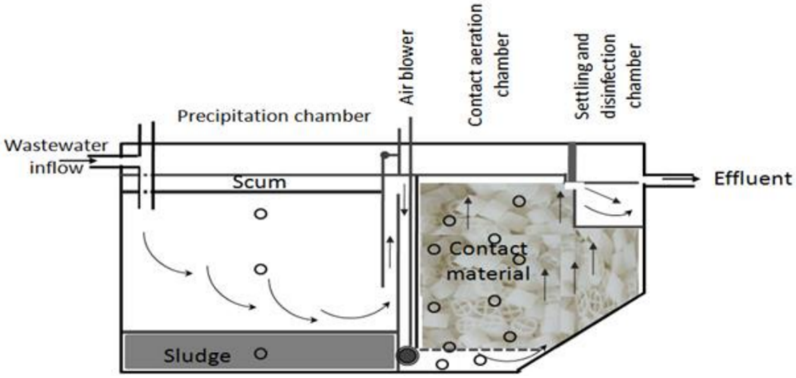

Figure 9: BCU Structure and Wastewater Flow Direction[103] (used with permission)

In a rural area near the Brazilian city of Campinas, where the average annual temperature is 22 °C[104] and there are approximately 1,895 hours of sunshine per year[104], such a system for 0.1 m^3/day[103] wastewater inflow is implemented.

Table 11: Wastewater Effluent Pollution Concentration Case Study BCU Campinas, Brazil [103]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	24.0	68.0
COD (mg/L)	58.0	37.4
TSS (mg/L)	13.0	77.2
TP (mg/L)	1.3	63.9
TN (mg/L)	34.0	52.1
FC (MPN/100ml)	410	98.9

A energy- and cost-effective variant of aerobic wastewater treatment are Passively Aerated Biological Filter (PABF) systems (see Figure 10), which utilize natural ventilation for aeration. Wastewater is pumped through a sprinkler system into compartments, where filter material provides a large surface for microbial growth, breaking down organic matter and pollutants, while particles are filtered out.[105]

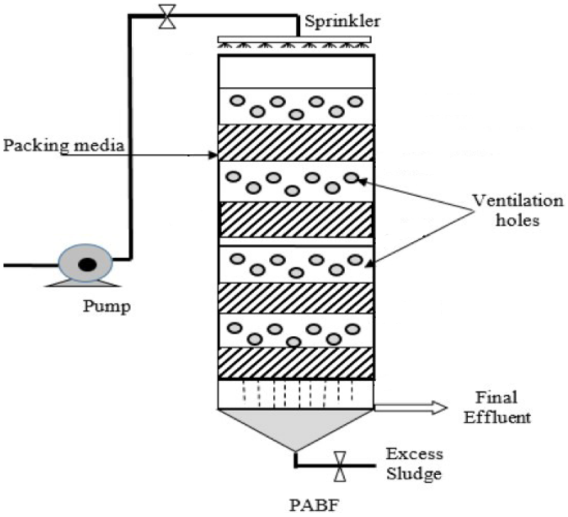

Figure 10: PABF Structure and Wastewater Flow Direction [106] (used with permission)

In a rural area north of the Egyptian capital Cairo, such a system was put into operation. The climatic conditions there are characterized by an average annual temperature of 22.5 °C[107] and 3,451 hours of sunshine[107]. The system is designed for a wastewater flow of 2 m^3/d[106].

Table 12: Wastewater Effluent Pollution Concentration Case Study PABF Rural Cairo Area, Egypt [106]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	13.0	85.0
COD (mg/L)	30.0	82.0
TSS (mg/L)	5.0	88.0
TP (mg/L)	2.2	38.0
TN (mg/L)	10.0	70.0

5.3 Case Study Analysis: Anaerobic Treatment Systems

Anaerobic wastewater treatment systems are particularly advantageous for application in developing countries compared to aerobic systems due to their significantly lower energy consumption and operational simplicity. Additionally, they require considerably less space than NTS[108]. Anaerobic systems generally necessitate post-treatment processes because the effluent quality from these systems alone is inadequate for direct discharge or reuse.[109]

An Up-Flow Anaerobic Sludge Blanket Reactor (UASB) (see Figure 11) is a common variant for the anaerobic wastewater treatment. In this system wastewater flows upward through the sludge[110], where microorganisms decompose the organic matter in the water and producing biogoas. The baffles ensure proper wastewater flow and solids separation[111].

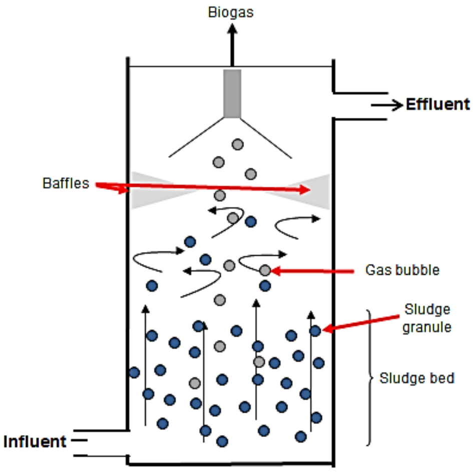

Figure 11: UASB Structure and Wastewater Flow Direction [112] (used with permission)

In the region around North Giza in Egypt, there is a decentralized wastewater system that relies on a UASB reactor. The wastewater flow rate in the rural region is approximately 2 m^3/day[113]. The average annual temperature there is approximately 21.2 °C[114] and the area receives an average of 2,880 hours of sunshine per year[114].

Table 13: Wastewater Effluent Pollution Concentration Case Study UASB North Giza, Egypt [113]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	66.9	65.7
COD (mg/L)	140.9	59.7
TSS (mg/L)	42.3	76.3
TP (mg/L)	2.5	37.5
TN (mg/L)	41.5	20.1
FC (MPN/100ml)	74,200	95.1

Anaerobic Baffled Reactor (ABR) (see Figure 12) operate similarly to their aerobic counterparts, consisting of multiple chambers under anaerobic conditions. With the aid of microorganisms, organic matter in the wastewater is decomposed. The baffles support solid separation.[115]

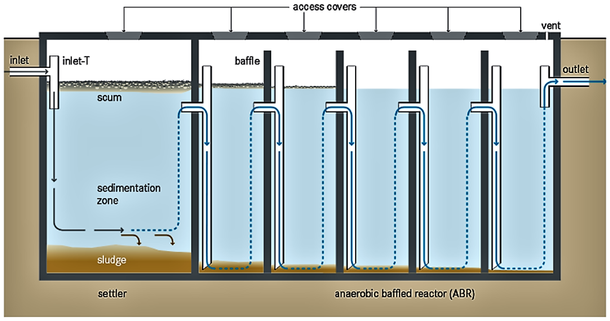

Figure 12: ABR Structure and Wastewater Flow Direction [116] (used with permission)

The region around Tehran, Iran, shows annual temperature of 22.6 °C[117] and 3,030 hours of sunshine[117]. There is a setup of an ABR system, with a wastewater flow rate of 0.1 m^3/day[118].

Table 14: Wastewater Effluent Pollution Concentration Case Study ABR Teheran, Iran [118]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	110.0	68.2
COD (mg/L)	290.0	59.3
TSS (mg/L)	237.2	54.5
TP (mg/L)	15.3	67.4
TN (mg/L)	51.25	19.2

A combined approach to increase efficiency[119], was implemented in the rural region around the city of Malang, Indonesia, where the average annual temperature is 23.7 °C[120] and 1,970 hours of sunshine[120]. The system treats 0.3 m^3/day of wastewater using an ABR and UASB.[121]

Table 15: Wastewater Effluent Pollution Concentration Case Study ABR and UASB Malang, Indonesia [121]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	26.0	88.0
COD (mg/L)	116.0	78.0
TSS (mg/L)	13.0	90.0
TP (mg/L)	5.0	34.0
TN (mg/L)	14.0	70.0
FC (MPN/100ml)	317	78.6

5.4 Case Study Analysis: Hybrid Systems

To achieve maximum flexibility and efficiency in wastewater treatment, the implementation of hybrid systems for decentralized wastewater treatment is recommended. These systems generally offer a good cost-benefit ratio.[122]

In developing countries and rural regions, STs are often used for wastewater treatment[123]. These STs primarily rely on anaerobic processes to break down organic matter and pollutants. However, STs alone are usually insufficient[124] for safe wastewater treatement and reuse or discharge into water bodies[125].

In the rural area of the Lower Jordan Rift Valley in Jordan, a variation of a classic ST is used for wastewater treatment. This Modified Septic Tank (MST) is designed for a wastewater flow of 1.2-2 m^3/day[126]. The image13 shows the structure of these STs. It is a hybrid system that combines an anaerobic chamber and an aeration chamber at the end to treat the wastewater as efficiently as possible.[126]

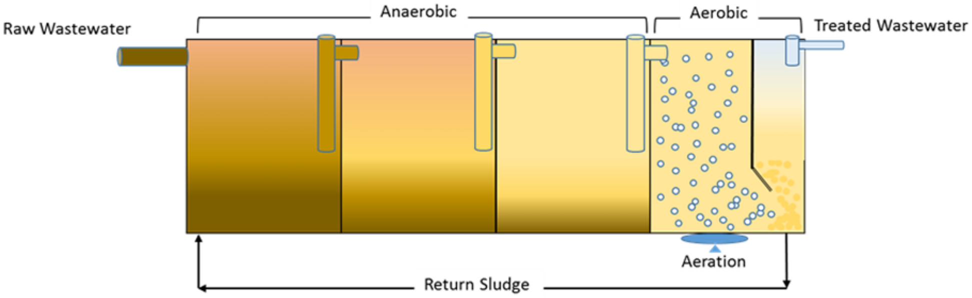

Figure 13: MST Structure and Wastewater Flow Direction [126] (used with permission)

The average annual temperature in the region is 17.3 °C and the average number of sunshine hours is approximately 3,500 per year.[127]

Table 16: Wastewater Effluent Pollution Concentration Case Study Modified Septic Tank Lower Jordan Rift Valley, Jordan [126]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	8.0	98.3
COD (mg/L)	55.0	94.0
TP (mg/L)	9.7	24.8
TN (mg/L)	46.6	59.1
FC (MPN/100ml)	26,000	98.0

This system is excellent for the removal of BOD and COD; however, both TP and FC levels do not fall within the legally acceptable range set by the Ethiopian government (see Table 1).[126]

In the Al-Kfair Village in Jordan a UASB reactor is combined with a VF-CW to treat the wastewater of the rural community for reuse. The flow rate of the system is 0.3 m^3/day[128]. The climate in that area is characterized by an average annual temperature of 17 °C[129] and 3,290 hours of sunshine per year[129].

Table 17: Wastewater Effluent Pollution Concentration Case Study UASB and VF-CW Al-Kfair Village, Jordan [128]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	4.1	97.0
COD (mg/L)	27.12	97.5
TSS (mg/L)	10.8	94.0
TP (mg/L)	0.33	98.0
TN (mg/L)	38.48	18.0
FC (MPN/100ml)	700	99.0

Another notable application of a hybrid system with CW is found near the Pakistani capital, Islamabad.[130] The climatic conditions there include an average annual temperature of 22.2 °C[131] and 2,950 hours of annual sunshine[131]. The system there consists of an ABR followed by a HF-CW. Subsequently, the water flows into a collecting pond and is then further treated through a FWS-CW.[130]

Table 18: Wastewater Effluent Pollution Concentration Case Study ABR, HF-CW, Collecting Pond and FWS-CW Islamabad Region, Pakistan [130]

Parameter	Effluent Concentration	Removal Efficiency (%)
BOD (mg/L)	35.0	82.3
COD (mg/L)	53.0	81.0
TSS (mg/L)	38.0	91.0
TP (mg/L)	2.1	76.0
TN (mg/L)	36.1	43.6
FC (MPN/100ml)	64	62.0

5.5 Selection for Techno Economical Analysis

Table19 shows the collected effluent concentrations of the considered parameters for the different technologies in the case studies and table20 displays the removal efficiencies. Green color marks the NTS, yellow represents the aerobic technologies, orange indicates the anaerobic systems and red highlights the hybrid solutions.

Table 19: Summary Effluent Pollution Concentrations Case Study Technologies

	Effluent Concentration					
	BOD (mg/L)	COD (mg/L)	TSS (mg/L)	TP (mg/L)	TN (mg/L)	FC (MPN/100ml)
WSP	4.5-117.0	51.0-457.5	18.0-220.5	0.11-7.4	0.01-17.4	12-810
CW	5.0-36.0	30.0-92.3	2.0-22.4	0.3-6.0	14.8-15.6	68-300
ABB	74.6	171.1	32.7	3.9	1.2	159
BCU	24.0	58.0	13.0	1.3	34.0	410
PABF	13.0	30.0	5.0	2.2	10.0	7,244,359
UASB	66.9	140.9	42.3	2.5	41.5	74,200
ABR	110.0	290.0	237.2	15.3	51.25	500,000
UASB+ABR	26.0	116.0	13.0	5.0	14.0	317
MST	8.0	55.0	126	9.7	46.6	26,000
UASB+CW	4.1	27.1	10.8	0.3	38.5	700
ABR+NTS	35.0	53.0	38.0	2.1	36.1	64

Table 20: Summary Pollutant Removal Efficiency Case Study Technologies

	Removal Efficiency					
	BOD (%)	COD (%)	TSS (%)	TP (%)	TN (%)	FC (%)
WSP	75.3-96.0	56.5-78.7	43.6-65.8	40.8-92.2	48.0-95.4	94.3-99.9
CW	79.0-98.3	77.2-95.0	53.2-99.5	40.0-54.3	48.1-80.0	92.7-99.9
ABB	95.1	93.9	97.2	96.1	94.3	99.9
BCU	68.0	37.4	77.2	63.9	52.1	98.9
PABF	85.0	82.0	88.0	38.0	70.0	36.9
UASB	65.7	59.7	76.3	37.5	20.1	95.1
ABR	68.2	59.3	54.5	67.4	19.2	99.9
UASB+ABR	88.0	78.0	90.0	34.0	70.0	78.6
MST	98.3	94.0	70	24.8	59.1	98.0
UASB+ CW	97.0	97.5	94.0	98.0	18.0	99.0
ABR+NTS	82.3	81.0	91.0	76.0	43.6	62.0

These case studies have already provided a preliminary filtering of suitable technologies. It is clear that aerobic treatment systems are not practical for use in the rural area of the Northern

Gondar Region in Ethiopia due to their high energy requirements[132]. NTS function effectively without energy when designed and constructed properly. By aligning system components with natural conditions, these systems harness the gravitational flow of liquids, eliminating the need for pumps[133]. Anaerobic components for decentralized wastewater treatment alone are often insufficient to achieve adequate treatment results and require post-treatment. In the presented case studies, this was also evident. Although effluent standards are generally met after post-treatment, as seen in some hybrid systems, this involves added complexity to the system.[134]

In conclusion, based on the case study analysis, NTS emerges as favorite among the technical preselecetion. However, a ST should be used for pre-treatment to enhance the overall effectiveness and maintain the functionality and longevity of the system[135]. In addition to the technical preselection, the following techno-economic analysis will also consider these monetary and socio-economic factors[136].

6 Techno Economical Analysis

The use of a TEA serves as an optimal tool to integrate the multidisciplinary fields of technology, economics and social aspects[137]. The data sets for this analysis were gathered through literature and case study research, as well as expert opinions (see Appendix C and D).

6.1 System Design Overview

Before the actual comparative analysis, the general system design must be determined. First, the common basic concept will be defined, followed by an explanation of the respective different technologies.[138]

Sanitation Facilities

A shared centralized toilet facility is planned. A survey form Mozambique demonstrated that such facilities, can significantly improve the quality of life compared to pit latrines and open defecation[139]. Data from Tanzania also revealed that shared toilet facilities among low-income populations are generally functional, safe and easier to maintain within a community setting[140]. Another decisive factor is that shared bathroom facilities is significantly more cost-effective than providing individual setups for each household[141].

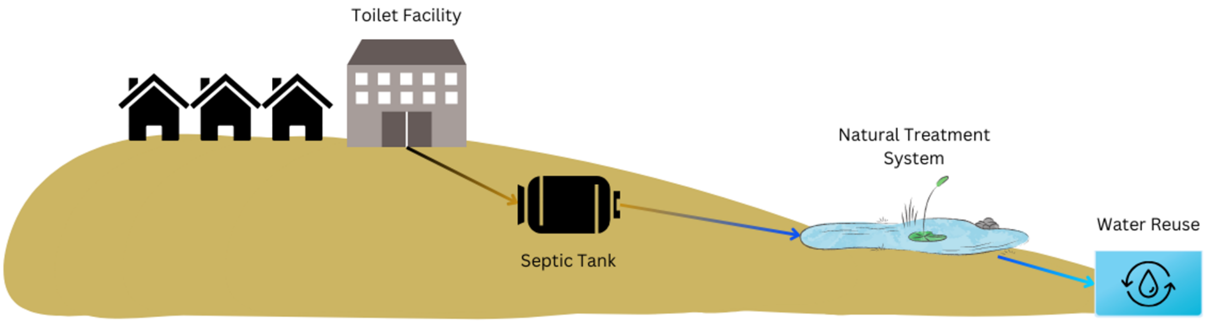

Figure 14: Schematic Representation of the Planned Design Concept and Components of the Decentralized Wastewater System (own illustration)

The general system layout is shown schematically in the Figure 14. The system is designed to operate without energy, utilizing gravity flow for wastewater transport. The settlement and particularly the toilet facility, is situated at a higher elevation than the ST, NTS and collection tank[142]. For the toilets themselves, gravity flow toilets should be used. These can operate without energy as long as the tank for flushing the toilet bowl is filled. This can be achieved for example by collecting rainwater or by manually refilling with treated wastewater.[143]

Local Conditions

To utilize gravity for water transport, the settlements in the rural area of the Northern Gondar Region should have certain slopes. A slope of at least 1 %[144] is necessary to create a functional gravity flow. This means there must be a height difference of one meter over a distance of 100 meters[144]. The villages in the region between Lake Tana and the city of Gondar and in the Northern Gondar Region, generally exhibit a certain elevation difference from the surrounding fields. This is illustrated in the Figure 15 using four example villages from the region[145]. The line connecting the three points is between 500 and 1000 meters[146].

Figure 15: Elevation Structure of Villages in the Observation Zone in Northern Gondar, Ethiopia (own illustration)

Another important point is the soil composition in the region. The soil is predominantly classified as Vertisols[147]. This soil structure, with its high clay content, makes excavation work more challenging, but it is still feasible[148].

Septic Tank

The design of the ST is based on the case study from the Sharquiya Governorate in Egypt (see Table 8), as the conditions and, in particular, the flow rate were very similar to those in the Northern Gondar Region[95]. The dimensions of the ST can be determined from Table 21.

Table 21: Dimensions of Septic Tank [95]

Septic Tank	
Parameter	Dimension
Length	6.5 m
Width	3.45 m
Depth	2.5 m

The ST should be installed at a depth of up to 3 meters[149] and constructed from concrete for durability, due to the soil composition[95]. However, a benefit of the Vertisol soil composition is its low permeability, providing more time to address leaks before wastewater can significantly seep into the ground[150]. Regular maintenance is still crucial. The tank should be inspected annually[151], with sludge removal every three to five years to ensure optimal functionality[152].

Scenario 1: Waste Stabilization Pond

Based on local conditions and the comparable flow rate, the sizing of the WSP system relies on the case study from Mzuzu, Malawi (see Table 5), as the system design has proven to be highly effective for wastewater treatment[75]. Since a ST is used as pre-treatment in the wastewater treatment system design, the use of an anaerobic pond becomes redundant[153]. The proposed system consists of a facultative pond followed by three maturation ponds, as depicted in Figure6 "c"[75]. The ST is necessary because, in the Malawi case study, the wastewater influent entering the WSP system has a similar pollution level to the wastewater effluent from the ST in the Sharquiya Governorate[95]. In designing the system, the Mzuzu case study will not be followed exactly, due to the different wastewater inflow rate[75]. Instead, the Gloyna method 3 will be used for sizing the facultative pond[154].

$$V = (3.5 \cdot 10^{-5}) \cdot (Q) \cdot (La) \cdot \left[\theta^{\,(35-T)}\right] (f) \cdot (f') \tag{3}$$

where,
V = Pond Volume (m^3)
Q = Influent Flow Rate (L/d)
La = COD (mg/L)
θ = Temperature Correction Coefficient = 1.085
T = Pond Temperature (°C)
f = Algal Toxicity Factor
f' = Sulfide Oxygen Demand

The influent flow rate is set at 6000 L/day, based on the daily wastewater inflow amount determined in Chapter 5 2. COD concentration is based on ST effluent characteristics from the Sharquiya Governorate, determined at 350 mg/L[95]. For pond temperature, an average daily minimum temperature of 13 °C is used, reflecting temperature fluctuations[32]. The algal toxicity factor quantifies the toxicity of a substance, such as wastewater or chemicals, on algae. For domestic wastewater, this value is 1[155]. The sulfide oxygen demand measures the oxygen required to oxidize sulfides in water or wastewater. This parameter corresponds to a value of 1[155] for wastewater with an SO_4 concentration of less than 500 mg/L [156], which includes domestic wastewater. This leads to the following calculation and result:

$$V = (3.5 \cdot 10^{-5})(6000\,L/d)(350\,mg/L)\left[\theta^{\,(35-13)}\right] \tag{4}$$

$$V = 442\,m^3 \tag{5}$$

The details for the design of the pond system can be found in Table 22. While the depth will be set at 1.2 meters[75], the aspect ratio for WSPs is generally 3:1[157]. For the dimensioning of the maturation ponds, the design is based on the case study from Malawi [75], where the maturation ponds are determined to have a volume that is 44 % of the volume of the facultative pond, maintaining a 3:1 ratio[75].

Table 22: Dimensions of WSP System [75][154]

Waste Stabilization Ponds				
Pond Type	Length	Width	Depth	Area
Facultative	33.5 m	11 m	1.2 m	368 m^2
Maturation 1	21 m	8 m	1.15 m	162 m^2
Maturation 2	21 m	8 m	1.1 m	162 m^2
Maturation 3	21 m	8 m	1.05 m	162 m^2

Scenario 2: Constructed Wetland

Similar to a WSP-System, the CW as a treatment method, can be operated without energy, making a HF-CW an viable system[158]. Satisfactory treatment results can be found in the case studies form Kothapally, India [91] and Sharquiya Governorate, Egypt[95], where wastewater inflows are similar. The selection of the plant species is also crucial. Vetiver grass has already been successfully used in CW systems in Ethiopia[159], due to its rapid growth, extensive root system and resilience to environmental changes[160].

For dimensioning of the CW, the Kickuth equation 6 is used, [161] with assumptions regarding the substrate depth of the pond based the case study from Egypt[95]. The filtration bed consists of gravel and sand and should have a depth of 0.6 to 1.0 meter[162] to allow for plant growth and root oxidation. The CW is assumed to be filled with a substrate mixture of sand and gravel to a depth of 0.8 meters[162] and a layer of of river rocks in the inlet and outlet zones measuring 1 meter x 10 meter x 0.8 meter respectively[163].

$$A_{CW} = \frac{Q \cdot (\ln C_{in} - \ln C_{out})}{k_{BOD}} \tag{6}$$

where,

A_{CW} = Surface Area of Bed (m^2)
Q = Average Daily Wastewater Inflow Rate (m^3/d)
C_{in} = Influent BOD Concentration (mg/L)
C_{out} = Effluent BOD Concentration (mg/L)
k_{BOD} = Rate Constant (m/d)

$$k_{BOD} = k_T d n \tag{7}$$

with,

$$k_T = k_{20} \theta^{\ (T-20)} \tag{8}$$

where,

k_{20} = Rate Constant at 20°C = 0.4
θ = Temperature Correction Coefficient = 1.085
T = Pond Temperature (°C)
d = Depth of Substrate (m)
n = Porosity of Substrate = 0.4

As in the calculation for the WSP system, a flow rate of 6 m^3 per day is assumed (see Equation 2). The BOD influent concentration of 180 mg/L is taken from the ST effluent results of the

Shaquiya Governorate case study[95]. The BOD effluent concentration of 22 mg/L[92] is based on the values achieved under almost identical climatic conditions in Ocotlán, Mexico.

The rate constant k_{BOD} describes the decay rate of BOD[164]. To obtain the value k_{BOD} the rate constant kt must be used. The value of k_t, however, is composed of k_{20}, which represents the decay rate at 20 °C ambient temperature[165]. For Ethiopia, this value is approximately 0.4[166]. Additionally, the temperature correction coefficient of 1.085 [154], used in the WSP calculation and a pond temperature of 13°C[32] are applied in order to obtain the value for k_t.

In the following k_t multiplied by the substrate depth of 0.8 meters[162] and the approximate porosity factor of 0.4 for the sand and gravel mixture[167], results in the value for k_{BOD}.

$$k_T = 0.4 \cdot 1.085^{(13-20)} = 0.226 \tag{9}$$

$$k_{BOD} = 0.226 \cdot 0.8 \cdot 0.4 = 0.07 \tag{10}$$

$$A_{CW} = \frac{6 \cdot (\ln(180) - \ln(22))}{0.07} \tag{11}$$

$$A_{CW} = 180\,\mathrm{m}^2 \tag{12}$$

Table 23: Dimensions of CW System [95]

Constructed Wetland Pond	
Parameter	Dimension
Length	18 m
Width	10 m
Depth	1 m
Area	180 m^2

6.2 Technical Analysis

6.2.1 Scenario 1: Waste Stabilization Pond

Maintenance needs

A key reason for failure of WSP systems is insufficient maintenance, which is crucial for long-term performance and effectiveness[168]. The positive aspect is that generally, not many trained personnel are needed. Tasks can generally be broken down into simpler activities like cutting grass, cleaning, or similar tasks. Regular check-ups should focus on sludge accumulation, vegetation growth and potential seepage issues.[169]

Tasks assigned to residents must be straightforward to perform and monitor, utilizing visual training and simple checklists. While workshops support understanding and effectiveness in community-based maintenance[170]. Training for maintenance should be community-based to ensure a widespread familiarity with the system. For example in an Indian village, local farmers harvesting the plants and clean the facilities independently, leading to high satisfaction and acceptance among the residents[171]. To regularly test water samples for pollution characteristics, a collaboration with the University of Gondar should be established, as the university has the facilities for such testing. Ideally, the local wastewater authority of the region should also be involved.[172]

Initially, fresh water from local sources, such as the Magech River or Lake Tana, should be used to fill the pond system[173].

Energy Requirements

Since WSP systems have the capability, the goal is to operate the system energy-autonomously. This can be achieved through the use of gravity and a tiered arrangement of the ponds. Additionally, the region's weather is characterized by abundant sunshine, which promotes photosynthesis and consequently aeration[174]. This enables a significantly higher breakdown of organic matter. Moreover, the Ultraviolet (UV) radiation helps to destroy pathogens. The combination of UV radiation, high average temperatures and oxygen results in a form of natural disinfection[175]. Maintenance also plays a crucial role in this context, allowing the complete elimination of external energy sources through manual upkeep and the use of hand tools[176]. In the worst-case scenario, if the gradient is insufficient or the water flow is not adequate, pumps might be needed. These pumps could be powered by solar panels, since sunlight is plentifully available in this region[177].

Scalability

The scalability in this analysis refers to the ability of the respective system to adapt to changes, such as an increased wastewater inflow due to population growth in the catchment area, without compromising the system's effectiveness[178]. In this context, WSP are relatively easy to modify. Existing ponds can be expanded, or additional maturation ponds can be constructed as needed. Modifying the existing ponds can involve increasing their depth or overall dimensions[179]. The primary limiting factor is the land requirement. Another limiting factor in scaling up WSP systems is the population size and the associated pollution load. WSPs are typically recommended for populations of up to 2,000 people[180]. Scaling to 2,000 people would require the facultative pond alone to be more than 3,600 m^2[154], which is approximately the size of half a football field.[181] The case study about the WSP-System near the Ethiopian City of Jimma (see Table 2) also shows that meeting regulatory standards becomes challenging with such large populations[66]. Excessive up-scaling of WSP systems generally leads to increased maintenance and energy requirements[182].

Sludge Management

Sludge management is a critical aspect of maintaining NTS, especially for WSP Systems, which are generally less hydraulically efficient than CWs. The sludge accumulates mostly from the sedimentation of suspended solids, bacteria and algae, complicating hydraulic control[183]. However, due to the pretreatment in the ST[184], the overall amount of solids in the water should be significantly reduced[61], typically requiring removal every 10-15 years.[169] It is important to note that in WSP systems, sedimentation is a predominant process, unlike in CW systems where filtration through the substrate is the primary mechanism. This results in a more rapid accumulation of sludge in WSP systems.[185]

Sludge management for WSP can be divided into three stages: desludging methods, sludge discharge and final disposal[186]. It is possible to remove the sludge while there is still water in the pond, but this method is up to 50 % more expensive[187]. Generally, the sludge can be reused as a fertilizer or as an energy source. As a fertilizer, it is mainly suitable for non-crop applications such as forestry and for energy production, the appropriate facilities for gas production must be available[188]. Burning is also an option, but the resources for this are limited. In some developing countries, sludge is used as a replacement or additive in cement or tar production[189]. In Ethiopia, the infrastructure for proper sludge disposal is still lacking and even in the capital Addis Ababa, sludge disposal is often inadequate[190]. To avoid such practices, it is recommended to dry and dewater the sludge in drying beds, as done in Senegal, where the dried sludge is utilized for fuel production[191].

Area

As previously mentioned, land use is a significant factor in NTS, as this type of decentralized wastewater treatment requires the most land area compared to other methods[192]. In the proposed dimensions (see Table 22), the total area amounts to approximately 850 m^2, which is roughly the size of two basketball courts[193]. However, this is only the net area; when considering construction and grading, additional land is required.

HRT/SRT

Since the expert survey indicated that HRT and SRT are of secondary importance (see Appendix C) for the implementation of decentralized wastewater treatment systems in developing countries, these parameters will also play a minor role in the analysis. Generally, the SRT for WSP has been addressed under the chapter on Sludge Management and is approximately 15 years[194]. The more important parameter here is the HRT. For facultative ponds, the HRT typically ranges from 5-20 days[194] and for maturation ponds, it ranges from 5-10 days[194]. However, given the relatively low inflow rate of the planned ponds, the HRT should be as long as possible in each pond[195].

6.2.2 Scenario 2: Constructed Wetland

Maintenance needs

CW, similar to WSP, are a type of wastewater treatment that considered low-maintenance [196]. The maintenance tasks for CW can be divided into the following categories: Scale-up O&M, Routine O&M, Long-term O&M and Monitoring[197]. For Scale-up O&M, similar to WSP, this involves initially planting the basin with the constructed filter bed and filling it with fresh water. Routine O&M tasks primarily consist of monitoring vegetation, sludge, substrate, water flow, odor and algae growth. Long-term O&M tasks mainly involve resolving potential blockages. Monitoring involves identifying and observing key pollution parameters to ensure the system's effectiveness.[197]

For both systems, reliable maintenance and community involvement is essential for their successful operation. However, the focus of the maintenance tasks differs between the systems[198]. Generally, WSP involve less complex daily tasks[195], primarily related to sludge and algae management. CW involve more complex tasks, including plant management, hydraulic dynamics and substrate health. Additionally, the monitoring frequency for CW is higher compared to WSP, which means that if maintenance frequencies become irregular, the WSP system tends to be less vulnerable to failure.[199]

Energy Requirements

CW can generally operate without external energy input, similar to WSP. It is essential to ensure adequate gradient to maintain water dynamics and flow. Maintenance tasks can be performed with manual tools and inspections can be done visually[200]. The cleaning processes within the system occur naturally: physical processes such as water flow and sedimentation are driven by gravity, biological processes involve the decomposition of organic matter by microorganisms found in the substrate and root zones and chemical processes like adsorption—binding of organic compounds to the CW surfaces—occur without additional energy input. Filtration through the substrate layers also requires no extra energy and oxygenation of the water is achieved through root respiration rather than additional aeration.[201]

Ensuring consistent water flow[202] is important to maintain the filtration efficiency and if necessary, pumps powered by solar energy could be used to address any deficiencies[203].

Scalability

Modifying CW systems is not as straightforward as with WSP systems. There are different approaches to managing changes. For instance, to address variations in pollution load, the substrate can be replaced or expanded, or a different plant species can be introduced into the wetland[204]. Scaling up CW systems is more complex in planning and execution compared to WSP, due to the more complex construction of CWs[205]. On the other hand, treatment efficiency of CWs can be more precisely controlled through modifications or expansion and required less additional land. If a CW is tailored to specific pollution loads, any adjustment would necessitate a complete reevaluation[206] of the system, which is simpler in the case of WSPs[207].

Sludge Management

Proper sludge management is vital for the effective operation of CW systems[208]. The general guideline is to remove sludge every 10-20 years[209], though this is partially modified due to the pretreatment in the ST, leading to a slower sludge accumulation[210]. The removal of sludge from CW systems is more complex and expensive than from WSP systems, as it involves the removal and replacement of substrate and plants for a complete cleaning[211]. Fortunately, CW systems are characterized by lower sludge accumulation due to their filtration process, rather than sedimentation. Therefore clogging of the filter medium must be prevented[212] and can be managed with specialized cleaning techniques[211]. Additionally, the use of a HF-CW system, a type of SSF system, results in very minimal to no sludge accumulation[213] on the substrate compared to surface flow systems.

Similar to WSP systems, CW systems face challenges with sludge disposal. Establishing drying beds to reduce the volume of the sludge and make handling easier[214], could not only address this problem but also contribute to resource recovery. The interesting aspect is the fact that sludge from the ST can indeed be treated in CWs. While it is generally feasible to stabilize and dewater sludge directly in a subsequent CW, this approach may reduce the treatment efficiency of the wetland system. Therefore, specialized Sludge Treatment CWs[215] should be used for this purpose. Trials in Brazil have shown that sludge from STs can be successfully further treated in CW systems. This, requires the optimal design of the CW system.[216]

Area

Similar to WSP systems, CW systems require a significant amount of land compared to other decentralized wastewater treatment methods[217]. However, generally and also according to Table 23, the net land area required for a CW system is significantly smaller than that needed for a WSP system. At $180\,\mathrm{m}^2$, the area required for a CW system is less than a quarter of that needed for a WSP system, roughly equivalent to half the size of a basketball court[193]. Although the land is state-owned, there are opportunity costs associated with the lost possibility of growing crops on that land. [218]

HRT/SRT

For the CW system, the SRT has also been addressed under the Sludge Management chapter. Generally, for both CW and WSP systems, the longer the HRT, the higher the expected treatment efficiency[219]. Typically, HRTs for CW systems range from 4-15 days[220]. However, given the relatively low wastewater inflow, it is advisable to aim for the higher end of this range.

6.2.3 Result Technical Analysis

Wastewater Effluent Characteristics

Table 24: MCA Wastewater Treatment System Pollutant Removal Efficiency

Pollutant	Mean Removal Efficiency (MRE) WSP (%)	Mean Removal Efficiency (MRE) CW (%)	Expert Weighting (EW) (%) ± Standard Deviation (SD)	WSP Weighted Performance Range (MRE*EW)	CW Weighted Performance Range (MRE*EW)
BOD	85.7	88.7	23.02 ± 10.4	11-29	11-30
COD	67.7	86.1	23.02 ± 10.4	9-23	11-29
TSS	54.7	76.4	17.83 ± 9.02	5-15	7-21
TP	66.5	47.2	9.16 ± 5.9	2-10	2-7
TN	72.1	64.1	11.35 ± 7.39	3-14	3-12
FC	97.1	96.3	15.65 ± 10.87	5-26	5-26
TOTAL				**35-117**	**39-125**

Table 24 presents a Multi Criteria Analysis (MCA) of both systems pollutant removal efficiency. The MCA is based on the results of the expert survey regarding the weighting of each pollution parameter. However, unlike in the expert survey, BOD and COD are listed separately, though with the same weighting. Due to insufficient data for a proper comparison of the systems, the parameters 'Pathogens', 'pH-Level' and 'Heavy Metals' are not considered. Nevertheless, the percentages allocated to these parameters were redistributed among the remaining parameters based on their weighting to ensure a meaningful comparison (see Appendix C).

The key findings regarding removal efficiency indicate that both WSP and CW systems are effective for wastewater treatment in developing countries[221]. Both systems demonstrate the ability to meet the regulatory effluent standards for Ethiopia and the ranges of their weighted performance overlap mostly[53]. The result of the MCA slightly favors the use of a CW system. The result is generally close but CW systems outperform especially in the highly weighted BOD, COD and TSS parameters

Furthermore, the removal efficiencies is to be considered in the context of a developing country. Where the goal is primarily on ensuring sanitation and the safe reuse of wastewater, which both treatment systems achieve.[222]

Technical Parameters

Table 25: MCA Wastewater Treatment System Technical Parameters

Parameter	Performance Ranking (PR) WSP	Performance Ranking (PR) CW	EW (%) ± SD	WSP Weighted Performance Range (PR*EW)	CW Weighted Performance Range (PR*EW)
Maintenance needs	5	4	25.81 ± 10.93	0.7-1.8	0.6-1.5
Energy Requirements	5	5	22.74 ± 10.09	0.6-1.6	0.6-1.6
Scalability	4	3	15.13 ± 9.4	0.2-1	0.2-0.7
Sludge Management	3	4	15.15 ± 5.97	0.3-0.6	0.4-0.8
Area	2	4	11.17 ± 7.19	0.1-0.4	0.2-0.7
HRT/SRT	2	3	10 ± 5.84	0.1-0.3	0.1-0.5
TOTAL				**2-5.7**	**2.1-5.8**

The expert survey weightings(see Appendix C) are used again for the technical parameter analysis in Table 25. Since the individual parameters can either not be quantified or are quantified in different units, a ranking scale from 0 to 5 points was used for weighting. A score of 0 represents very unfavorable performance, while 5 represents the optimal case[223]. Simple maintenance tasks[224] and energy-free operation[225] score higher, with 5 being the ideal rating. Scalability is evaluated based on how well the system can adapt to changing conditions, with better and easier adaptability receiving a higher rating[226]. Shorter intervals for sludge removal are considered advantageous for sludge management[227]. Systems needing less area[228] and shorter HRT/SRT[229] are also rated higher.

According to this ranking, the two systems overlap significantly in their evaluation once again, while the CW system can reach the higher end of the evaluation range. Both systems are assumed to operate without additional energy, thus receiving the highest performance ranking for enery requirements[230]. The WSP system is notably distinguished by the low difficulty level of its routine maintenance tasks[195] and tends to perform better in scalability[231].

The CW system has advantages in terms of sludge management and HRT/SRT. Considering land use, comparing Tables 22 and 23 clearly shows that the CW system occupies less than a quarter of the expected area required by the WSP system. [232]Additionally, CW systems offer the potential for sludge treatment in the future, whereas WSP systems produce a larger volume of sludge, leading to challenges in pumping and proper disposal.[215]

6.3 Economical Analysis

6.3.1 Scenario 1: Waste Stabilization Pond

Initial Capital Costs

A major cost driver in the installation of WSP systems is all expenses related to construction costs. These inital capital costs primarily include excavation, pond lining, labor costs and material costs[233]. For a meaningful comparison between WSP systems and CW systems, quantitative data based on case studies and literature is consulted. Supported by the current material costs[234][235][236][237] of local Ethiopian distributors, retrieved in August 2024. This means that the results provide an estimate for the expected costs when implementing such a system[238]. All costs reported were inflation adjusted to 2024 values using the Consumer Price Index factor provided by the United States Bureau of Labor Statistics[239].

A study analyzing the capital costs of decentralized wastewater treatment systems for communities with fewer than 1,000 inhabitants in France found that the capital cost for WSP systems are approximately $ 132 per person [195] in the catchment area. In the research case, this would amount to approximately $ 26,400. In a World Bank analysis, WSP systems are estimated to cost approximately $ 150[224]. This results in a total cost of around $ 30,000 for the system in Ethiopia. However, this approach remains generalized and lack specificity for the context[240].

The construction period is challenging to determine due to its site-specific nature. However, for a estimate, a case study from New Zealand is referenced, where a pond was constructed in similarly clay-rich soil. In this case, the construction of a significantly larger pond than the planned facultative pond took two months.[241] However, this project did not include lining or piping. Therefore, for the WSP system with one facultative pond and three maturation ponds, including piping and lining, a construction period of 6-9 months is anticipated. For further assumptions, a construction period of nine months is used.[241] To estimate the labor costs, the higher end of the average income range of an Ethiopian citizen from a rural area is used, which is approximately $ 77 per month.[242]

$$Labor\ Cost\ Construction \ = Average\ Labor\ Cost\ per\ Month\ \cdot Worker\ \cdot Months \tag{13}$$

$$\$\,77 \cdot 15 \cdot 9 = \$\,10,400 \tag{14}$$

Considering the expected construction period and a workforce requirement of 10-20 people, the approximate labor cost for the entire construction period is around $ 10,400[242]. This cost estimate also takes into account the wage differences between unskilled workers and, for example, project managers[243]. For a more detailed cost analysis of the ponds, a case study on pond construction from Brazil is referenced. The dimensions of the faculative pond is similar but generally about 10 % smaller and the maturation ponds are about 30 % smaller, so a respective cost increase per pond is anticipated.[244]

$$Excavation\ Cost\ Facultative\ Pond\ = Excavation\ Cost\ Facultative\ Pond\ + 10\,\% \tag{15}$$

$$\$\,2,074 \cdot 1.1 = \$\,2,282 \tag{16}$$

$$Excavation\ Cost\ Maturation\ Ponds\ = (Excavation\ Cost\ Maturation\ Pond\ + 30\,\%\ ) \cdot 3 \tag{17}$$

$$(\$\,1,620 \cdot 1.3) \cdot 3 = \$\,6,318 \tag{18}$$

$$Excavation\ Cost\ Ponds\ = Cost\ Facultative\ Pond\ + Cost\ Maturation\ Ponds \tag{19}$$

$$\$\,2,282 + \$\,6,318 = \$\,8,600 \tag{20}$$

With these additional details, the construction costs for all four ponds amount to approximately $ 8,600, this includes the cost for the excavator, hammer, trucks and manual labor tools[244]. The ponds should also be sealed with a Polyvinyl Chloride (PVC) liner[245], and pipelines between the individual components of the system must be installed.

$$Lining\ Area\ Facultative\ Pond\ = Base\ Area\ + Wall\ Area \tag{21}$$

$$Base\ Area\ Facultative\ Pond\ = 33.5\,\mathrm{m} \cdot 11\,\mathrm{m} = 368.5\,\mathrm{m}^2 \tag{22}$$

$$Wall\ Area\ Facultative\ Pond\ = 2 \cdot (33.5\,\mathrm{m} \cdot 1.2\,\mathrm{m}) + 2 \cdot (11\,\mathrm{m} \cdot 1.2\,\mathrm{m}) = 106.8\,\mathrm{m}^2 \tag{23}$$

$$Lining\ Area\ Facultative\ Pond\ = 368.5\,\mathrm{m}^2 + 106.8\,\mathrm{m}^2 = 475.3\,\mathrm{m}^2 \tag{24}$$

$$Lining\ Area\ Maturation\ Pond\ = (Base\ Area\ + Wall\ Area\ ) \cdot 3 \tag{25}$$

$$Base\ Area\ Maturation\ Pond\ = 21\,\mathrm{m} \cdot 8\,\mathrm{m} = 168\,\mathrm{m}^2 \tag{26}$$

$$Wall\ Area\ Maturation\ Pond\ = 2 \cdot (21\,\mathrm{m} \cdot 1.1\,\mathrm{m}) + 2 \cdot (8\,\mathrm{m} \cdot 1.1\,\mathrm{m}) = 63.8\,\mathrm{m}^2 \tag{27}$$

$$Lining\ Area\ Maturation\ Ponds\ = (168\,\mathrm{m}^2 + 63.8\,\mathrm{m}^2) \cdot 3 = 695.4\,\mathrm{m}^2 \tag{28}$$

$$Total\ Lining\ Area\ = Area\ Facultative\ Pond + Area\ Maturation\ Ponds \tag{29}$$

$$475.3\,\mathrm{m}^2 + 695.4\,\mathrm{m}^2 = 1170,7\,\mathrm{m}^2 \tag{30}$$

$$Total\ Lining\ Cost\ \ =\ Lining\ Area\ \cdot Lining\ Cost\ per\ \mathrm{m}^2 \tag{31}$$

$$1171\,\mathrm{m}^2 \cdot 3,5\,\$/\mathrm{m}^2 = \$\,4,098 \tag{32}$$

$$Total\ Piping\ Cost\ \ =\ Piping\ Length\ \cdot Piping\ Cost\ per\ \mathrm{m} \tag{33}$$

$$35\,\mathrm{m} \cdot 67\,\$/\mathrm{m} = \$\,2,345 \tag{34}$$

$$Total\ Lining\ +\ Piping\ Cost\ \ =\ Piping\ Cost\ + Lining\ Cost \tag{35}$$

$$\$\,4,098 + \$\,2,345 = \$\,6,443 \tag{36}$$

The cost for lining and piping the ponds is amounting to around \$ 6,450 and based on the current cost for a PVC liner in Ethiopia for 3.5 $\$/\mathrm{m}^3$[237]. In the calculation of the maturation ponds, only Maturation Pond 2 was used as a reference point, as the depth difference of the ponds will be balanced out by considering a depth of 1.1 meters (see Table 22). The piping material has a diameter of 200 millimeters with a thickness of 2.2 millimeters and costs 67 \$/m[236]. Additionally, 40 meters of piping were calculated, as a distance of 10 meters is assumed between the ST and the facultative pond, as well as between maturation pond 3 and the collection basin. A distance of five meters is assumed between each pond.

$$TCC\ \ = Average\ Labor\ Cost\ + Excavation\ Cost\ Ponds + Lining\ \&\ Piping \tag{37}$$

$$\$\,10,400 + \$\,8,600 + \$\,6,450 = \$\,25,450 \tag{38}$$

Labor costs for a 9-month construction period included, the capital costs also amount to Total Construction Cost (TCC) of approximately \$ 25,450[244]. This is based on an average 40-hour work week, as is the case in Ethiopia, with eight hours per day, five days a week[246]. In comparison an additional cost breakdown from a case study in Greece is considered. After adjusting for the pond size differences, the estimated construction costs amount to approximately \$ 35,100[247]. Including the labor costs, the total sum is around \$ 45,000. This results in a value of \$ 225 per person in the respective catchment area, while in Ethiopia, it is expected to remain at $ 126 per person, which makes sense as such construction in a stronger economy like Greece[248] is associated with higher costs. This finding is consistent when compared to the $ 132 per person in France[195] and the general value from the World Bank of $ 150 per person[224].

Accordingly, after reviewing and adjusting the available case study information, it can be estimated that the costs for the WSP system in rural Ethiopia will be approximately $ 20,000-$ 30,000, with $ 30,000 being considered in the further stages of this economical analysis.

Operational Cost

The O&M costs primarily cover pond maintenance, monitoring and maintaining cleanliness. A study of different decentralized wastewater treatment systems in France found that O&M costs for WSP systems are approximately $ 5 per person and year[195], totaling around $ 1,000 per year for the Ethiopian system. It should be noted that France is considered a highly developed country[249]. Therefore, the actual O&M costs for Ethiopia will certainly be lower. In the World Bank analysis, WSP systems are categorized as a low-cost option regarding O&M costs, with expenses of less than $ 3 per person and year[224], resulting in approximately $ 600 anually, excluding sludge disposal. A Greek case study estimates cost of $ 3.80 per person per year[250], or $ 760 annually for the entire Ethiopian system, while in Brazil, costs were around $ 2 per person per year, equaling $ 400 in total. Another data collection from Germany also yields an result of $ 2.50 per person per year[251], which adds up to $ 500 in total. Therefore, based on the available case study data, O&M costs in the range of $ 400-$ 1,000 per year can be expected. Given that costs in a developing country like Ethiopia are generally lower, the expenses are likely to be on the lower end of this range. This will also depend on whether the maintenance is effectively carried out by the local community or if someone needs to be employed long-term to ensure the system's upkeep[252]. Since both France[249] and Germany[253] qualify as developed countries, the subsequent analysis will be based on the Brazilian value of $ 400[169]. This figure is considered the most appropriate for Ethiopia, as it is expected to be closer to local conditions and falls below the World Bank's average[224].

LCC

LCC can be viewed as a combination of Initial Capital Costs and O&M costs[254]. WSP systems and other NTS are considered to be long-lasting due to their reliance on natural processes for wastewater treatment and their simple construction[255]. However, to provide a comparable benchmark, the lifespan of this system is estimated to be around 50 years[256], which aligns with the average lifespan of wastewater treatment facilities in general. This estimate takes into account that while the core natural treatment processes can be very durable, individual components of the system may require maintenance or replacement over time[257]. With a lifespan of 50 years for the system, sludge will need to be removed at least three times[169] and the lining will likely need to be replaced once. Piping is generally very durable, when no chemicals are added to the process, so replacement is not included[258].

The average sludge accumulation per person ranges from 0.021-0.036 m^3 per person per year[259]. For simplification an rounded volume of 0.04 m^3 per person is assumed[54].

$$\textit{Total Annual Sludge Accumulation} \;= \textit{Average Sludge Accumulation} \cdot \textit{Number of People} \tag{39}$$

$$0.04\,\mathrm{m}^3/\mathrm{year} \cdot 200 = 8\,\mathrm{m}^3/\mathrm{year} \tag{40}$$

$$\textit{Total Sludge Accumulation} \;= \textit{Total Annual Sludge Accumulation} \;\cdot \textit{Cleaning Interval} \tag{41}$$

$$8\,\mathrm{m}^3/\mathrm{year} \cdot 15\,\mathrm{years} = 120\,\mathrm{m}^3 \tag{42}$$

This results in approximately 8 m³ per year for a population of 200 people, leading to a total of 120 m³ over a 15-year cleaning interval. However, the ST is expected to have an efficiency of 50-70 % [95] in removing sludge-forming contaminants. With a lower efficiency of 50 % [260][126], the resulting sludge accumulation would amount to 60 m³. The sludge disposal costs in the area of the capital, Addis Ababa, are given within a relatively large range of 9-36 \$/m³[261]. For the calculation, a midpoint of 22.5 \$/m³ is used, as Addis Ababa offers better infrastructure but is also generally considered wealthier[262].

$$\textit{Sludge Disposal Cost} \;= \textit{Disposal Cost per } \mathrm{m}^3 \cdot \textit{Sludge Amount} \tag{43}$$

$$22.5\,\$/\mathrm{m}^3 \cdot 60\,\mathrm{m}^3 = \$\,1,350 \tag{44}$$

$$\textit{Total Sludge Disposal Cost} \;= \textit{Disposal Cost per Cleaning Interval} \cdot \textit{Cleaning Intervalls} \tag{45}$$

$$\$\,1,350 \cdot 3 = \$\,4,050 \tag{46}$$

Over the entire lifespan, sludge removal costs could amount to approximately \$ 4,100[263]. Additionally, another lining replacement should be considered. Based on the previous results 32, the costs for this replacement are approximately \$ 4,100.

$$\textit{Additional Cost} \;= (\textit{Sludge Disposal} \;+ \textit{Liner Replacement}) + 25\,\%\ \textit{of Cost} \tag{47}$$

$$(\$\,4,050 + \$\,4,100) \cdot 1.25 = \$\,10,187.5 \tag{48}$$

Combining these factors, additional costs of around $\$\,10{,}190$ can be expected, when considering a 25% contingency for possible waste or equipment.[244]

$$Average\ Daily\ Salary \ = \frac{Average\ Montly\ Salary}{Working\ Days\ per\ Month} \tag{49}$$

$$\frac{77\,\$}{20} = \$\,3.85 \tag{50}$$

$$Additional\ Labor\ Cost \ = Worker\ \cdot Days\ \cdot Daily\ Average\ Salary \tag{51}$$

$$15 \cdot 10 \cdot \$\,3.85 = \$\,577.5 \tag{52}$$

Including the rounded labor costs in the amount of $\$\,580$ for 15 worker and approximately 10 days total additional costs of $\$\,10{,}770$ can be assumed. The initial capital costs, when combined with the O&M costs and additional expenses over the system's lifespan, amount to approximately $\$\,60{,}770$ in the expected scenario. Decommissioning costs are intentionally excluded from this calculation[264], as reliable data is not available in the referenced literature.

It is important to consider the social factor, particularly with regard to land use[265]. For WSP systems, functionality largely depends on the acceptance and cooperation of the community, as demonstrated in the installation of such a system in India. The population was eventually convinced of the positive aspects and financial benefits of using treated wastewater for irrigation and sludge for fertilizing fields[266]. Although land in Ethiopia is officially owned by the state, farmers are still allowed to cultivate it on a long-term basis[267]. If farmers in this agriculturally driven area feel that their livelihoods are threatened, countermeasures must be taken[268]. In Kenya, for instance, affected individuals were compensated through financial payments or alternative land and the importance of sanitation was emphasized[269].

Table 26: Total Cost Overview WSP System

Cost Factor	Estimated Costs
Initial Capital Cost	$ 30,000
O&M Cost	$ 20,000
Sludge Management	$ 4,050
Liner Replacement (with Contingency)	$ 6,140
Labor Cost (without Construction)	$ 580
TOTAL LCC	**$ 60,770**

6.3.2 Scenario 2: Constructed Wetland

Initial Capital Costs

The initial capital costs for implementing CW systems, similar to those for WSP systems [233], primarily include planning, design, excavation, earthworks, construction materials and labor. The analysis of decentralized wastewater treatment in France also provides a general monetary estimate for the capital costs of CW systems. The cost is estimated at $ 210 per person[195], which amounts to approximately $ 42,000 for the planned project. The World Bank analysis, on the other hand, classifies CW systems in the same category as WSP systems and quantifies the initial cost at $ 150 per person.[224], which translates to a total cost of approximately $ 30,000. In a case study from Brazil, the capital costs for such a CW system were estimated at $ 38,000[270].

Regarding the construction time, a case study from the Greek island of Crete is analyzed, the excavation time for a CW with the same volume[271] took one month. The soil conditions in this region are also characterized by a high clay content[271]. Therefore, when adjusting for the scale of the facility in the Northern Gondar region, an excavation period of two months can be expected, considering the local infrastructural conditions and experience with construction projects in Ethiopia[272]. After adjusting for inflation, construction work costs approximately $ 4,000. This includes the cost for the excavator, hammer, trucks and manual labor tools over a two month period[271]. For this type of wastewater treatment, lining the pond and installing piping are important for ensure a controlled water flow.

$$\textit{Lining Area} \;= \textit{Base Area} \;+ \textit{Wall Area} \tag{53}$$

$$\textit{Base Area} \;= 18\,\mathrm{m} \cdot 10\,\mathrm{m} = 180\,\mathrm{m}^2 \tag{54}$$

$$\textit{Wall Area} \;= (2 \cdot 10\,\mathrm{m}^2) + (2 \cdot 18\,\mathrm{m}^2) = 56\,\mathrm{m}^2 \tag{55}$$

$$\textit{Lining Area} \;= 180\,\mathrm{m}^2 + 56\,\mathrm{m}^2 = 236\,\mathrm{m}^2 \tag{56}$$

$$\textit{Total Lining Cost} \;=\; \textit{Lining Area} \;\cdot \textit{Lining Cost per}\,\mathrm{m}^2 \tag{57}$$

$$236\,\mathrm{m}^2 \cdot \$\,3.5 = \$\,826 \tag{58}$$

$$\textit{Total Piping Cost} \;=\; \textit{Piping Length} \;\cdot \textit{Piping Cost per}\;\mathrm{m} \tag{59}$$

$$20\,\mathrm{m} \cdot 67\,\$/\mathrm{m} = \$\,1,340 \tag{60}$$

These activities are estimated to cost $2,170, with a duration of one month and they include costs for the lining amounting to $830 and for the piping amounting to $1,340. It is assumed that 20 meters of piping are required to establish the 10 meter connections[271] between the ST and the pond, as well as between the pond and the collection basin. Another important construction component is the substrate installment.

$$Amount\ Sand\ and\ Gravel \ = Lenght \ \cdot Width \ \cdot Depth\ Substrate \tag{61}$$

$$16\,\mathrm{m} \cdot 10\,\mathrm{m} \cdot 0.8\,\mathrm{m} = 128\,\mathrm{m}^3 \tag{62}$$

$$Amount\ River\ Rocks \ = Lenght \ \cdot Width \ \cdot Depth\ Substrate \tag{63}$$

$$2\,\mathrm{m} \cdot 10\,\mathrm{m} \cdot 0.8\,\mathrm{m} = 16\,\mathrm{m}^3 \tag{64}$$

$$Cost\ Sand\ and\ Gravel\ Mix\ 3:1 \ = \frac{3}{4} \ \cdot Cost\ Gravel \ + \frac{1}{4} \ \cdot Cost\ Sand \tag{65}$$

$$\frac{3}{4} \ \cdot \$\,36 + \frac{1}{4} \ \cdot \$\,27 = \$\,33.75 \tag{66}$$

$$Cost\ Sand\ and\ Gravel \ = Amount\ Sand\ and\ Gravel \ \cdot Cost\ Sand\ and\ Gravel \tag{67}$$

$$128\,\mathrm{m}^3 \cdot 33,75\,\$/\mathrm{m}^3 = \$\,4,320 \tag{68}$$

$$Cost\ River\ Rocks \ = Amount\ River\ Rocks \ \cdot Cost\ River\ Rocks \tag{69}$$

$$16\,\mathrm{m}^3 \cdot 10\,\$/\mathrm{m}^3 = \$\,160 \tag{70}$$

$$Total\ Substrate\ Cost = Cost\ Sand\ and\ Gravel + Cost\ River\ Rocks \tag{71}$$

$$\$\,4,320 + \$\,160 = \$\,4,480 \tag{72}$$

Filling the CW in the pre-defined volume with river rocks, gravel and sand is expected to incur costs of around $4,480. The mixture ratio of gravel to sand is 3:1[273]. The cost per cubic meter for the mixture, amounting to 33.75 $\$/\mathrm{m}^3$, is based on the current Ethiopian market prices for gravel[234] and sand[235]. The cost for river rocks is 10 $\$/\mathrm{m}^3$[274].

Based on the given dimensions, approximately 800 plant seedlings will be required for the CW basin. Based on the specification that five plants should be planted per square meter[275].

$$Amount\ Plants\ = Surface\ Pond\ without\ Inlet\ and\ Outlet\ Area \cdot 5\ Plants\ per\, \mathrm{m}^2 \tag{73}$$

$$160\,\mathrm{m}^2 \cdot 5\,\mathrm{Plants/m}^2 = 800 Plants \tag{74}$$

$$Cost\ Plants\ = Amount\ Plants \cdot Cost\ per\ Plant \tag{75}$$

$$800\ Plants \cdot 1.11\,\$/\mathrm{Plants} = \$\,888 \tag{76}$$

Planting the system is estimated to cost nearly $ 890[276]. The price estimate is based on a source from Europe, thus lower prices are anticipated in Ethiopia, because the use of Vetiver grass is quite prevalent[277].

The combined cost and time for adding substrate and planting in Greece took about one month[271]. In theory, the construction is based on 15-20 people working on the project.

$$Labor\ Cost\ Construction\ \ = Average\ Labor\ Cost\ per\ Month\ \ \cdot Worker\ \ \cdot Months \tag{77}$$

$$\$\,77 \cdot 20 \cdot 6 = \$\,9,240 \tag{78}$$

Assuming that there more complex planning through experts in the design phase, the labor costs[242] for a six months construction period are rounded upwards and estimated at 9,240 $. Based on the data from the CW installation in Bulgaria, an additional 10 % [278] is added to the Initial Capital Cost for planning, design and approval of the project concept.

$$TCC\ \ = (Labor\ \ + Constuction\ Pond + Lining\ \&\ Piping\ \ + Substrate\ \ + Plants\ ) \cdot 10\,\% \tag{79}$$

$$(\$\,9,240 + \$\,4,000 + \$\,2,170 + \$\,4,480 + \$\,890) \cdot 1.1 = \$\,22,858 \tag{80}$$

Thus, the TCC of a CW system with the previously described dimensions would amount to a total initial capital cost of approximately $ 23,000. In the analysis of other case studies from small communities in Central America, which are very similar in scale to the planned HF- CW system, costs amount to $ 106 per person[279]. Projected onto the Ethiopian model, this corresponds to total costs of approximately $ 21,200. For a CW system in Jiangsu Province, China, the total costs for a CW system with a capacity of 100 m^3/day amounted to approximately $ 49,000[280]. In a rural area of Jordan, on the other hand, a CW system with a water flow rate of 0.25 m^3/day was built with investment costs of approximately \$ 2,000[281]. A HF-CW system constructed in Nepal and designed for a flow rate of 10 m^3[282] with a total area of approximately 375 m^2. While the soil structure[283], local infrastructure and development Of construction industry[284] bears similarities to Ethiopia, it required initial capital cost of approximately \$ 40,000[282]. Therefore the installation of the CW system can realistically be expected to cost in the range of \$ 21,000-\$ 40,000[285]. In the subsequent cost analysis, an initial capital cost of \$ 30,000 is assumed, considering the results of the calculation and the case studies from Nepal[282], Brazil[270] and Central America[279].

Operational Cost

The labor required for the O&M of CW systems is relatively minimal, as the general objective is to have the system operated by the community as much as possible[91]. As a general guideline, maintenance costs for CW systems are estimated to be 1-2 % [286] of the construction costs. In the case of the Ethiopian system, this would amount to approximately \$ 300-\$ 600 per year. The O&M costs from the French Case Study are estimated at \$ 6.10 per person per year[195], which totals approximately \$ 1,230. The World Bank analysis of operational costs reveals that CW systems are rated with a low average concerning O&M costs. This indicates that the costs per person per year are less than \$ 3[224], resulting in annual total costs of approximately \$ 600. In another study from Belgium, the approximate O&M costs for a 250 m^2 HF-CW system are estimated at around \$ 1,400[287]. However, this analysis is based on experiences from Belgium, a highly developed country[288]. Therefore, lower costs can be expected in Ethiopia. This observation aligns with the findings from a data collection study conducted on HF-CW system in the Czech Republic, where annual O&M costs were reported to be approximately \$ 1,500[289]. After adjusting the dimensions to fit the system in Ethiopia, the construction of a HF-CW system in the developing country Kenya, resulted in an annual O&M cost of \$ 600[290]. Upon reviewing the available case studies, the annual O&M costs for HF-CW systems were found to range from \$ 300-\$ 1,500. However, it is expected that in a developing country such as Ethiopia[16], these costs would likely fall towards the lower end of the range. Therefore, the analysis will use the O&M costs from Kenya[291], amounting to \$ 600[290].

Life Cycle Cost

The LCC determination for CW Systems, aims to provide an overview of the monetray costs regarding the installation over the system's entire lifespan[292]. In addition to capital and O&M expenditures, the environmental and socio-economic impacts will also be considered[293].

In order to generate a comparable analysis, a systems lifespan of approximately 50 years[294] can be expected. With appropriate maintenance and adherence to operational standards, the piping infrastructure in CW systems is expected to remain functional for up to 50 years[294]. It is anticipated that throughout the system's operational lifespan, the lining will require replacement once[295].

The substrate is a key component[83], which plays a essential role in maintaining the system's overall performance. Therefore, clogging of the filter medium must be prevented[296]. Unfortunately, there are few long-term studies on the performance of CW systems. However, depending on the solid load of the wastewater being treated and the effectiveness of the pretreatment, it can be expected that a gradual decline in efficiency may occur after 10-15 years of operation[211], due to clogging of the filter media. One of the most expensive methods to clean the substrate, is to excavate the gravel, wash it and replace it, which guarantees continued functionality but costs 100-116 $\$/\mathrm{m}^2$[232] and requires a long-term shutdown of the system. Another option is to use chemicals like hydrogen peroxide, which, poses health and safety risks and costs approximately 8–11 $\$/\mathrm{m}^2$[232]. A more cost-effective and increasingly popular method is the use of earthworms for cleaning[297]. This method costs about 1 $\$/\mathrm{m}^2$[232] and requires no specialized knowledge. However, is the most time-consuming and also necessitates a system shutdown[211]. The use of earthworms is a practical solution, especially since they are native to Ethiopia and readily available[298].

$$Unclogging\ Cost \ = Cost\ per\,\mathrm{m}^2 \cdot Amount\ Substrate\ \cdot Unclogging\ Frequency \tag{81}$$

$$1\,\$/\mathrm{m}^2 \cdot 144\,\mathrm{m}^2 \cdot 5 = \$\,720 \tag{82}$$

The total cost for cleaning the filter medium over the system's lifespan is estimated at approximately \$ 720, assuming it is done five times[211]. With the installation of a ST for pretreatment and the regular unclogging, it can be assumed that sludge accumulation will be minimal. Therefore sludge removal costs are excluded[210]. An additional plant replacement is also factored in, costing \$ 890[276].

Replacing the liner after some time is more complex than in WSP systems,[299] involving the careful removal reinstalling of the substrate and plants. Since there is no available information on the costs associated with replacing the lining material, the calculation includes the lining material costs of \$ 830[237], plus theoretical costs for new substrate and plants, which amount to \$ 4,480[234][235] and \$ 890[276] respectively.

$$Liner\ Replacement\ Cost \ = (Lining\ Material + Substrate + Plants) + 25\,\%\ of\ Cost \tag{83}$$

$$(\$\,830 + \$\,4,480 + \$\,890) \cdot 1.25 = \$\,7,750 \tag{84}$$

This results in a total cost for replacing the basin liner of approximately \$ 7,750[237], including a 25 % buffer for potential wastage or machinery.

$$Additional\ Labor\ Cost \ = Worker\ \cdot Days\ \cdot Daily\ Average\ Salary \tag{85}$$

$$20 \cdot 10 \cdot \$\,3.85 = \$\,770 \tag{86}$$

Adding potential labor costs of \$ 770[242], the total expense can be estimated at around \$ 8,270.

This estimate assumes the work of 20 workers over 10 days. By selecting Vetiver grass as the plant in the system, not only is a species native to Ethiopia being utilized, but it also ensures that the plants will not need to be replaced very often during the lifespan of the system[300]. However, regular trimming of the plants should be performed to maintain optimal performance[301].

Under the stated assumptions, it can be projected that, the total LCC amount to $ 70,130, without decommissioning costs[302].

Also the potential for cost recovery through the use of sludge as fertilizer or the reuse of treated water for irrigation or toilet flushing has not been considered for either system. This is due to currently lacking infrastructure and expertise. In this context, CW systems are also promising due to the additional potential to produce biofertilizer[303] from the plants used in CW systems.

The advantage of CW systems compared to WSP systems is, of course, the reduced land area required[304]. Additionally, there is a somewhat paradoxical aspect: due to the higher complexity of the CW system, there is often greater confidence in the effectiveness of the treatment mechanisms, compared to the more nature-based treatment approach of the WSP system[305]. A survey on CW construction in Sweden revealed that most farmers are willing to convert their land to CW if the land is not highly productive and if appropriate compensation is provided[306]. Similar findings were observed in Kenya, where farmers were compensated with alternative land for using their land for wastewater treatment purposes[269]. Community acceptance can therefore be expected to be higher for CW systems compared to WSP systems[307].

Table 27: Total Cost Overview CW System

Cost Factor	Estimated Costs
Initial Capital Cost	$ 30,000
O&M Cost	$ 30,000
Unclogging	$ 720
Plant Replacement	$ 890
Liner Replacement (with Substrate + Plant Replacement and Contingency)	$ 7,750
Labor Cost (without Construction)	$ 770
TOTAL LCC	**$ 70,130**

6.3.3 Result Economical Analysis

Table 28: Comparison Wastewater Treatment System Economical Parameters

Cost Factor	Estimated Costs WSP	Estimated Cost CW
Initial Capital Cost	**$ 30,000**	**$ 30,000**
O&M Cost	**$ 20,000**	**$ 30,000**
Sludge Management	$ 2,100	\
Unclogging	\	$ 720
Plant Replacement	\	$ 890
Liner Replacement (with Contingency)	$ 8,400	$ 7,750 (Substrate + Plant Replacement included)
Labor Cost (without Construction)	$ 540	$ 770
TOTAL LCC	**$ 60,770**	**$ 70,130**

The WSP system emerges as the more cost-effective solution, though certain assumptions in the cost parameters, require careful consideration. Sludge management significantly impacts the total LCC[195]. If sludge accumulation in the WSP system occurs more rapidly[308], costs for both systems will rise. Additionally, it is assumed that the substrate in the CW system will be renewed; if this is not necessary, costs for the CW system may decrease[211]. Similarly, the choice of liner material also affects costs[245]. Due to the high clay content in the soil, it might be considered to abstain from the usage of a liner to reduce costs, though this carries the risk of wastewater contaminating groundwater[309]. Despite these considerations, the WSP system consistently shows lower costs, mainly due to its simpler design and easier routine maintenance tasks[310]. The WSP system is adversely affected by the opportunity costs associated with the large land area required for the wastewater system. These costs can be up to four times higher compared to the corresponding CW system in terms of land area alone.[311]

As an MCA would not really enhance the relevance of the cost comparison, this analysis was dispensed with. Instead, two additional sensitivity analyses were conducted, due to specific assumptions made during the price evaluation. Graphics 16 and 17 each present a tornado diagram highlighting the key cost drivers for the CW and WSP systems[312]. For each parameter, a cost range was established based on the case studies, consisting of the maximum (most expensive) value, the base value determined in the analysis and the minimum value. Subsequently, the analyses considered both the least expensive scenario for each parameter as well as the most expensive scenario for each parameter, , while all other parameters were set to their base values.

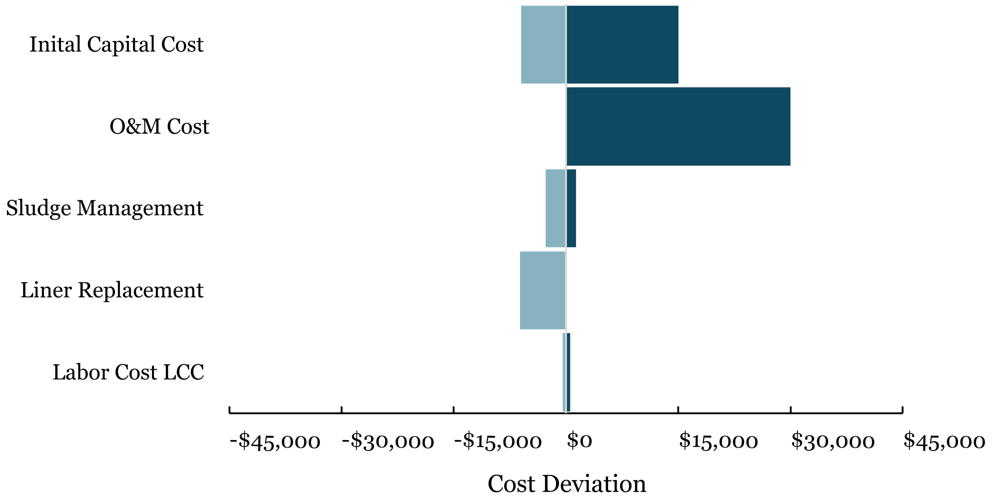

Figure 16: Cost Range among Main Cost Factors for WSP System with TEA Values as Base Case (own illustration)

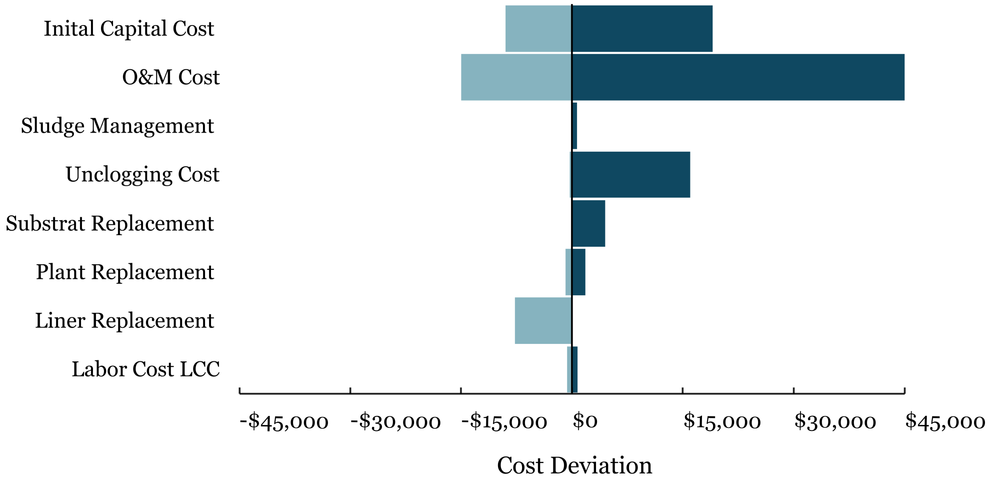

Figure 17: Cost Range among Main Cost Factors for CW System with TEA Values as Base Case (own illustration)

For sludge management in WSP systems, the best-case scenario assumes three sludge removals, while the worst-case scenario includes four cleaning intervals. For CW systems, the best case assumes no cleaning, while the worst case includes one cleaning event. Liner replacement for CW also includes the cost of new plants and substrate. Unclogging, a concern specific to CW systems, is included as a cost factor only for these systems. In the best-case scenario, worms are used for cleaning three times, while the worst-case scenario involves a complete washing of the substrate. For CW systems, the best case assumes no replacement of substrate or plants, while the worst case assumes one substrate replacement and three plant replacements. Labor costs are consistently based on a daily wage of $ 3.85[242]. In the best-case scenario, both systems require five workers for a total of five additional workdays, which are not covered under O&M or initial capital costs. In the worst-case scenario for WSP systems, 20 workers are needed for 15 days, while CW systems require 20 workers for 20 days to address the potential need for experts due to the more complex CW system. The tornado diagrams clearly show that initial capital and O&M costs, accumulated over 50 years[256], are significant cost drivers for both systems and must be closely monitored.

Additionally, a Monte Carlo analysis was conducted to assess the range in which the costs identified in the analysis are likely to fall. A simulation was performed, utilizing the established price range for each parameter. For each iteration, a random value was selected within the defined range for each parameter, which was then combined with the randomly selected costs of the ranges of the other factors. This process generated 5,000 potential LCC values for each system. Based on this simulation, an estimation can be made using the histograms 18 and 19 with respect to the LCC values determined in the analysis.[313]

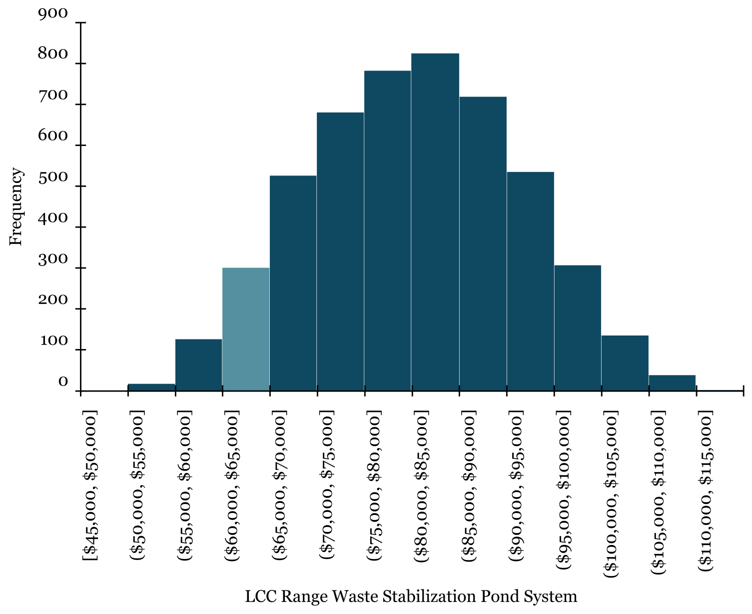

Figure 18: Frequency of LCC Range of WSP Systems with Highlighted Value from TEA (own illustration)

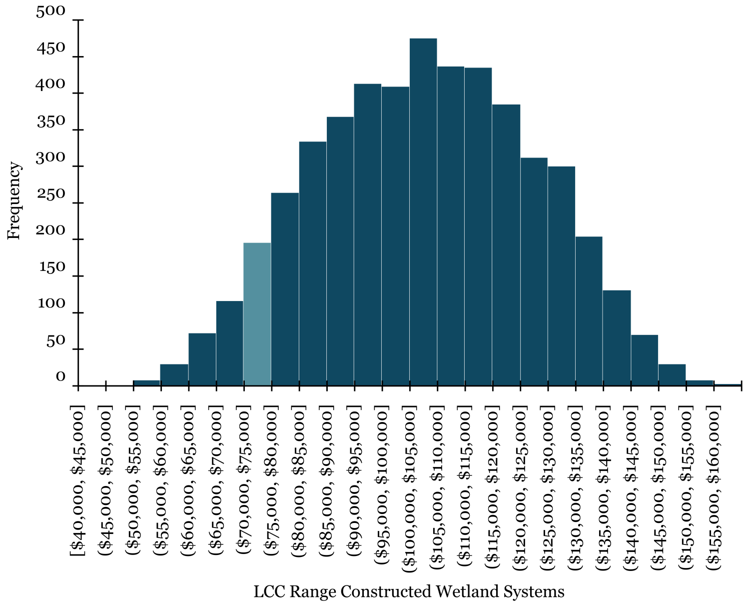

Figure 19: Frequency of LCC Range of CW Systems with Highlighted Value from TEA (own illustration)

The results are consistently found within the highlighted spectrum. Although certain parameters for the CW systems were estimated at slightly higher costs compared to the WSP systems in the economical analysis, the overall comparison reveals that both systems fall within a similar cost spectrum. Both systems' LCC are located in the lower quarter of their respective histograms, as indicated by the highligthed bins. The positioning within the comparatively low-cost segment is logical, as the LCC in a developing country such as Ethiopia is expected to be lower.

Thus, it can be concluded that both systems offer competitive options for decentralized wastewater treatment in rural Ethiopia, with WSP systems showing a slight advantage in cost-effectiveness.

7 Discussion

This work examined the feasibility of decentralized wastewater treatment systems for rural communities in developing countries based on a comparative TEA. The focus of the study was on rural Ethiopia, specifically in the Northern Gondar Region between Lake Tana and the city of Gondar. Due to the complexity and the wide variety of possible methods for decentralized wastewater treatment, a detailed case study analysis was conducted, focusing on treatment efficiency after considering the local conditions. It was particularly important that the case study projects had similar external conditions to the region in Ethiopia. Key factors included daily wastewater inflow, solar radiation, temperature and the classification of the wastewater as domestic. It was determined that NTS, compared to more energy-intensive methods of wastewater treatment, can achieve satisfactory results in terms of treatment quality, especially when they closely resemble the local conditions in Ethiopia (see Table 19 and Table 20). This insight is significant because rural areas in developing countries and especially in Ethiopia, often have unreliable or no access to electricity[314]. A wastewater treatment system that does not rely on additional energy, like a NTS, is highly preferable, particularly since the pollutant concentrations in the effluent not only comply with Ethiopian regulations but also compare well with other treatment methods. Therefore, after the technical pre-selection of the decentralized wastewater treatment methods, the TEA focuses on WSP and CW systems.

However, since the two systems differ in terms of effluent characteristics, technical and economic parameters, the TEA was conducted comparatively to demonstrate the feasibility of each system and their performance relative to one another. To achieve this in a quantifiable and comparable manner, two potential systems were sized based on recognized calculations (see 3 and 6) and successful case studies.

In order to obtain a scientifically meaningful analysis, an expert survey was conducted (Appendix C). The responses of 49 experts from six continents, both from academic and professional backgrounds, were collected. This resulted in a weighting of the predefined parameters in the evaluation sections, namely, pollutant characteristics of the wastewater, technical parameters and economic factors. Based on these weightings, a MCA was carried out for each section and the TEA was quantified. During an expert interview conducted with an Non-Governmental Organization (NGO) expert from Bremen Overseas Research and Development Association (BORDA), it became clear that the financing of wastewater systems in developing countries is one of the greatest challenges (see Appendix D). As a result, a Tornado diagram (see Figure 16 and Figure 17) was performed for the expected total LCC of both systems to identify the main cost drivers and a Monte Carlo analysis (see Figure 18 and Figure 18) was also carried out to confirm the financial comparability of the systems based on the respective cost structure.

Several aspects emerged from the evaluation of the MCA. First, three parameters from the expert survey were not considered in the final TEA and MCA: heavy metals and pH level for the effluent characteristics and job creation for the economic parameters. This is because heavy metals and pH-level received the lowest weighting in the expert survey and most case study data either did not include these parameters or, in the case of heavy metals, a detailed analysis would have been too extensive as it would require addressing all types of heavy metals[315]. The parameter of job creation was excluded as it also received the lowest weighting in its section and ideally, the system would be operated by the community itself[316]. The weightings were therefore redistributed evenly across the remaining parameters for the MCA.

In conclusion, the TEA and MCA do not provide a clear picture. Although the CW system performs as expected in terms of treatment efficiency and technical parameters, the WSP proves to be more cost-effective, as anticipated. However, it is not only the quantifiable data that should be considered in decision-making, but also social acceptance. Acceptance is a crucial point. The region in question is heavily agricultural, with fields, which serve as the main income source for farmers, typically located near villages[317]. While it has been noted that land in Ethiopia is state-owned[267] and can be made available for projects beneficial to the population, achieving broad acceptance for a project requiring a significant amount of land might be challenging[318]. This consideration strongly favors the CW system, as it requires much less land, thereby reducing opportunity costs associated with the loss of potential farmland[319]. Additionally, the seemingly more complex setup of a CW system, with its vegetation and substrate layering, tends to receive higher acceptance[305]. In contrast, the WSP system, which occupies significantly more land and appears much simpler in structure, could undermine confidence in the system's effectiveness and the use of treated water[320].

The case study analysis produced an interesting and unexpected result: NTS can indeed compete with more energy-intensive wastewater treatment methods in terms of treatment efficiency. However, it is important to note that the highest treatment efficiency results, as seen in the tables, were achieved through the combination of an NTS system with a septic or settling tank[97]. As a result, a pre-treatment in the form of a ST was also planned for the theoretical decentralized wastewater model for Ethiopia. These findings highlight that NTS in decentralized wastewater systems in developing countries are not only alternative methods to conventional aerobic and anaerobic treatments, but also stand-alone system models with significant benefits, independent of electrical power supply. This demonstrates the relevance of NTS as fully-fledged, not merely provisional, solutions in such contexts. However, the wide range of efficiency results also underscores the importance of careful planning for these systems, with particular attention to natural influences, as their performance is significantly affected by climatic conditions and changes[321]. This further shows that efficient wastewater treatment in economically disadvantaged areas can be achieved through natural processes, without chemical addition. The simplicity of O&M for these systems and opens the door for strong community involvement. However, the expert interview made it clear that the long-term success of such a project depends on consistent and thoughtful maintenance. It was already highlighted that this can be achieved primarily through clear and regular community training. Regular maintenance should be documented using a checklist. Given the high illiteracy rate of over 50 % in rural Ethiopia[322], this documentation can be supported by illustrations showing best and worst practices[323]. This approach could save money and emphasize the importance of system functionality to the population, fostering greater acceptance of sustainable wastewater treatment[324]. In the case of implementing multiple systems in this area, consideration could be given to hiring a full-time paid staff member to oversee the general management of these facilities and conduct workshops for residents[325].

The use of a liner in both system constructions is debatable. On one hand, the soil in the region contains a high amount of clay, which can work as natural sealing. As in the 16th century in Venice, Italy, underground water reservoirs were sealed with clay[326]. On the other hand, the expert interview recommended not fully sealing the soil, which could lead to significant cost savings in both systems and potentially avoid the need for complex liner replacement.

This work aims to serve as a novel blueprint for assessing the feasibility of decentralized wastewater systems in rural areas of developing countries. Through a combination of case study comparisons, TEA and MCA, supplemented by expert opinions from both academic and practical professionals, as well as an identification of cost drivers through Tornado diagram and Monte Carlo analysis, this blueprint offers new insights. Current literature on evaluating decentralized wastewater treatment methods in developing countries often references the dependency on local conditions, but mostly these conditions are either not sufficiently considered or not integrated into a comprehensive framework that includes multiple systems.

Nonetheless, this work is limited to data collected from case studies with similar initial conditions to those found in the Ethiopian region. Field studies could provide further clarification if the blueprint narrows down to one or a few system options. The financial assessment of this work focused primarily on Initial Capital Costs and O&M Costs, relying on a pricing range based on calculations and comparisons with data from countries in similar financial situations. The sensitivity analysis and histogram demonstrated that while costs may vary, both systems fall within a similar price range when directly compared. Another limitation of the financial assessment is that the analysis focused solely on the systems themselves. The installation of sanitary facilities, STs, or a collection basin for wastewater reuse was not considered. This was done to narrow down the evaluation and make the comparison clearer, as both systems share the same initial conditions. However, these factors must, of course, be taken into account in an actual project calculation. Additionally, the evaluation of the analysis parameters from the expert survey revealed significant fluctuations in individual weightings, particularly highlighted by the high standard deviations.

The feasibility and practicality of the systems in the rural Ethiopian context were undoubtedly confirmed. NTS systems stand out for their sustainability, as they imitate natural processes. Moreover, cultural sensitivity, as addressed in the expert interview, is considered in the choice of the CW system, as it does not require large areas of land and utilizes locally available resources such as Vetiver grass for planting and sand, gravel and river rocks for construction.

Furthermore, there are gaps to be addressed in the future, particularly concerning sludge management, water reuse and electricity supply. First, it must be determined whether sludge from the ST can be sustainably disposed. Additionally, if the CW system is positively received by the population, the use of sludge treatment wetlands could be considered[208]. Water reuse presents a challenge, as it must be ensured that the water is clean enough for agricultural use and it is necessary to determine at what intervals[327] the water will be distributed for irrigation. Another issue is the power supply. Although the functionality of gravity flow should be ensured, the system's performance could be improved by using solar-powered pumps[328]. These pumps could also return treated water to the sanitation system, allowing it to be used for toilet flushing[329], thus reducing the dependency on rainwater collection through rooftop cisterns and manual toilet refills[330].

The expert interview also revealed that securing funding plays a crucial role, especially for what initially appears to be a purely loss-making venture like wastewater treatment. Government bodies, international aid organizations, and private investors need to be convinced of the importance of proper wastewater treatment[50]. A detailed project description is essential for this, including a realistic and transparent breakdown of costs[331]. Additionally, the benefits of water reuse, the potential for fertilizer production from sludge, and the opportunity costs arising from long-term environmental degradation must be taken into account.

8 Conclusion and Outlook

This study aimed to answer the research question: Which technical and economic factors significantly influence the implementation of decentralized wastewater systems in developing countries? It also sought to illustrate how decentralized wastewater systems differ in terms of effectiveness, efficiency and affordability and to assess the overall feasibility of decentralized wastewater treatment systems in the rural context of developing countries. It is clear that decentralized wastewater treatment systems are not only an alternative for these regions but currently the only viable solution to ensure proper wastewater management. Choosing the appropriate method requires a thorough analysis of the specific locality. A key aspect in this process is the assessment of technical requirements. The main factors include whether the local population, who will live in the area and be served by the system, is capable of maintaining the facility themselves or whether, from an economic perspective, it makes sense to hire someone for the job. Additionally, the energy supply and the system's energy demand are crucial points. Precision is key here, as rural areas in developing countries often have either unreliable or no connection to the power grid, making it essential to accurately assess the energy requirements for effective planning. In terms of treatment efficiency, it is difficult to determine which pollutant parameter is more important to remove than others, as it depends on the interaction of all key parameters. However, the efficiency of removing benchmark parameters such as BOD, COD, and TSS carries particular weight. For the economic analysis, it is crucial not only to focus on the initial capital costs but to consider a comprehensive view of the estimated total costs over the entire lifecycle of the respective system. Since securing funding for development projects is particularly complex for rural populations in developing countries, a detailed breakdown and realistic assessment of the costs are equally important.

The combination of case study analysis, TEA, MCA and further economic analysis, supported by expert surveys and interviews, has shown that a NTS systems is the best choice for rural communities in the Northern Gondar Region of Ethiopia. In a specialized comparison of NTS systems, CW systems prove to be the better choice over WSP systems. The Monte Carlo and sensitivity analyses revealed that both systems have the potential to minimize specific cost drivers with proper handling, resulting in significant cost savings. Conversely, poor planning or inadequate maintenance can lead to significantly higher costs. Overall, NTS systems are cost-effective and particularly energy-efficient methods for decentralized wastewater treatment in developing countries. It is essential to implement some form of pre-treatment to achieve the highest possible treatment efficiency.

A particularly decisive factor in the decision-making process is land use, which has both technical and socio-economic implications. In an agricultural region like Ethiopia, where most people earn their livelihood directly from farming, it is difficult to gain acceptance for the use of the large land areas required for WSP systems. Additionally, the resources needed for CW systems, such as Vetiver grass for planting and sand, gravel and river rocks, are locally available in Ethiopia. This does not mean that WSP systems are not a good solution for decentralized wastewater treatment; rather, these systems should ideally be implemented in areas with less fertile soil, but where sufficient land is available. Their use is often found near industrial plants.

In general, NTS can not only be used as an alternative to conventional wastewater treatment systems. Their efficiency in wastewater treatment is quite comparable to that of conventional anaerobic and aerobic systems, even though the processes in NTS are less precisely to be controlled. Therefore, NTS also offer a viable method for wastewater treatment in industrialized countries, provided that sufficient space is available. However, these systems should only be implemented for communities up to a certain size, as larger populations may lead to a decline in overall performance. This is particularly important in countries with stricter wastewater effluent limits.

The implementation of decentralized wastewater treatment can significantly contribute to improving public health in rural areas of developing countries. Additionally, the more frequent expansion of these systems can enhance the community's understanding of sustainable and safe wastewater management in the long-term, representing a significant step towards achieving the SDG.

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List of Abbreviation

ABB	Aerobic Baffled Bioreactor
ABR	Anaerobic Baffled Reactor
AWP	Average Wastewater Production
BCU	Biological Compact Unit
BOD	Biological Oxygen Demand
BORDA	Bremen Overseas Research and Development Association
COD	Chemical Oxygen Demand
CW	Constructed Wetland
EW	Expert Weighting
FC	Fecal Coliforms
FWS	Free Water Surface
HF-CW	Horizontal Flow-Constructed Wetland
HRAP	High Rate Algal Pond
HRT	Hydraulic Retention Time
LCC	Life Cycle Cost
MCA	Multi Criteria Analysis
MST	Modified Septic Tank
NGO	Non-Governmental Organization
NTS	Natural Treatment Systems
PABF	Passively Aerated Biological Filter

O&M	Operation and Maintenance
PVC	Polyvinyl Chloride
SD	Standard Deviation
SDG	SDG(Sustainable Development Goals)
SRT	Sludge Retention Time
SSF	Subsurface Flow
ST	Septic Tank
TCC	Total Construction Cost
TEA	Techno Economical Analysis
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UASB	Up-Flow Anaerobic Sludge Blanket Reactor
UV	Ultraviolet
VF-CW	Vertical Flow-Constructed Wetland
WHO	World Health Organization
WSP	Waste Stabilization Pond

Appendix

A Most Common Decentralized Treatment and Disposal Methods

Natural Treatment System

The NTS are generally regarded as a cost-effective method of wastewater treatment, which makes their use particularly attractive for developing countries. A simple pond system is the simplest form of NTS. [332] Naturally occurring wetlands as well as CW and WSP can function as treatment ponds and are considered the simplest form. These systems combine treatment based on soil materials, plants and microorganisms. NTS can be operated both aerobically and anaerobically.[333] The processes of this treatment method consist of sedimentation, filtration, nitrification, denitrification, solar radiation, assimilation by flora and biodegradation. In addition to biological processes, chemical and physical methods such as precipitation and adsorption can be used.[334] In general, these systems achieve satisfactory wastewater quality. They are best used in regions with a lot of available land and little capital. The undeniable advantage of these systems is the low energy consumption during operation and the generally low maintenance. However, in addition to a large surface area, NTS also require a longer HRT. They can also cause unpleasant odors. Nevertheless, the wide availability of natural materials makes them a good choice, especially in warm tropical and subtropical regions. The effectiveness of this method of decentralized wastewater treatment also depends heavily on the correct training and level of knowledge of those responsible for operating.[335]

Aerobic Systems

Aerobic decentralized wastewater systems use oxygen in combination with microorganisms to break down organic matter. These systems use either forced aeration or mechanical aeration devices.[336] Examples of aerobic systems include the PABF, the BCU and ABB.[335] The compareable small landuse of aerobic systems is an advantage of aerobic decentralized wastewater treatments compared to NTS. While NTS require a large area, aerobic systems can be operated on a much smaller area. They can also achieve a very good quality of treated water, but come with a higher energy requirement.[337] In general, aerobic systems are considered high performance systems as they have a short SRT and HRT.[338] These systems are mainly used for wastewater with a chemical oxygen demand of less than 1,000 mg/L, which applies to domestic wastewater. However, trained personnel are required to operate these systems and regular maintenance is necessary to prevent clogging of the aeration devices and mechanical failures. The high SRT also leads to frequent disposal of sludge.[339]

Anaerobic Systems

In contrast to aerobic systems, which require oxygen, anaerobic systems function without oxygen. In these systems, anaerobic bacteria are used to break down organic compounds and produce methane and carbon dioxide in the process. This is why they are often used in biogas plants to generate energy. [340] Anaerobic decentralized wastewater systems can therefore be used as a source of energy. Compared to their aerobic counterparts, these plants have lower energy requirements and are considered cost-effective.[341] However, this method leads to biological treatment with less organic and nutrient removal. In addition, it takes longer for an anaerobic system to become fully operational, whereas aerobic systems are typically faster to start up. [342] This results in longer retention times for wastewater and sludge. In addition, odor nuisance can occur and these systems are highly dependent on temperature. If it is too cold, the bacteria work too slowly, while too high temperatures can destroy them. In contrast, aerobic systems are more resistant to temperature fluctuations.[343] Anaerobic treatment methods include e.g. ABR and UASB.[335] These systems are particularly suitable for wastewater with a high degree of contamination, i.e. with a chemical oxygen demand (COD) of more than 4,000 mg/L. As the quality of the effluent is not so high and secondary treatment is often required, these systems are often used in combination with other wastewater treatment methods.[344]

Hybrid Systems

In order to ensure that the wastewater is cleaned as efficiently as possible, the various wastewater systems could be combined in order to combine all the individual advantages.[345] For example, the use of anaerobic systems is often followed by aerobic systems to optimize the effluent quality. By using NTS in combination with aerobic and anaerobic treatment, on the other hand, the energy input can be reduced, resulting in a smaller ecological footprint.[346] Another good example of hybrid systems are STs, or more precisely, MST. These utilize a system of anaerobic and aerobic chambers to best combine the energy efficiency of the anaerobic approach with the treatment efficiency of the aerobic approach.[347] In general, hybrid systems are more stable and more ecological than stand-alone system solutions. Nevertheless, many hybrid systems are characterized by correspondingly high operating costs. Obviously, these combined decentralized systems also require specially trained personnel.[345]

B Detailied Definition Analysis Parameter

Wastewater Effluent Characteristics

BOD

The BOD is essentially the amount of molecular oxygen that organic matter in wastewater requires for biological oxidation. In other words, BOD is a parameter that indicates the amount of dissolved oxygen consumed during the decomposition of organic material by aerobic bacteria in wastewater. This process results in the breakdown of biodegradable organic matter into water and CO_2.[348] The BOD concentration is measured over a fixed period of time using a standardized unit. This parameter is expressed in milligrams of oxygen per liter of sample, typically over an incubation period of five days at a temperature of 20°C. Generally, the lower the concentration of BOD, the less organic matter and microbial organisms are present in the wastewater effluent.[349] In natural bodies of water, BOD levels typically remain below 1 mg/L, while moderately polluted bodies of water may exhibit values ranging from 2-8 mg/L. Most wastewater treatment plants aim for BOD levels of 20 to 30 mg/L in their effluent wastewater stream, though this often necessitates discharge into a flowing body of water to ensure optimal dilution.[350] The European Union set the limits for BOD in wastewater to 25mg/L when discharged into water bodies.[351]

COD

The COD is another parameter used to assess the degree of pollution in the water under consideration. COD measures the total oxygen consumption required to break down all organic and inorganic contaminants through chemical oxidation without the assistance of microbes.[352] Unlike BOD, COD measures not only the oxygen demanded by organisms but also everything that can be oxidized in the wastewater.[353] Hence, the value of COD is always higher than the corresponding BOD value for the water being analyzed. Surface water typically has a range of 5-20 mg/L. In comparison, untreated municipal wastewater has a COD value ranging from 300-1000 mg/L.[354] The EU has set a guideline of a maximum of 125 mg/L for wastewater discharge.[355] Elevated levels of BOD and COD typically result in a reduction of dissolved oxygen within the water body where the wastewater is discharged. This reduction, in turn, leads to the onset of anaerobic conditions, which further damages the ecosystem of the water body extensively.[353]

TSS

Another commonly used parameter to determine the level of pollution in wastewater is TSS. TSS are defined as solid particles suspended in water that can be captured by a filter.[356] The consequences of high pollution levels in wastewater include deterioration of water quality and depletion of fish stocks. This parameter is measured by determining the weight of the filter with the residues of TSS in difference to the weight of the filter without residues.[357] While the guidelines for Total Suspended Solids (TSS) vary depending on the nature of the wastewater, the European Union establishes a benchmark requiring a minimum removal of 50% of the wastewater.[351]

FC

Special attention should be given to pathogens such as FC and Enterococcus. Fecal contamination of water or wastewater can stem from various sources, including livestock operations, wildlife and, naturally, human excretions.[358] Enterococcus bacteria are found in their highest concentrations in human excretions. This bacterium has become a recognized indicator of human contamination in water alongside FC.[359] This contamination is problematic because these bacteria can cause gastrointestinal illness, which can have dramatic consequences, especially in developing countries.[360] The unit for determining the bacterial count is MPN/100 mL. This stands for "Most Probable Number" per 100 milliliters and represents a statistical estimate of the bacteria in a sample based on probability theory.[361]

Phosphorus

The removal of TP in wastewater is primarily important to prevent the eutrophication of the receiving water body. Eutrophication is described as the undesirable enrichment of nutrients in water bodies, leading to harmful plant growth and adverse effects on the ecosystem within the water body. It is important to emphasize that, particularly for small-scale wastewater treatment systems, there are currently very few technological approaches available for the removal of phosphorus. [362] One of the main sources of phosphorus enriched in wastewater originates from human excrement. Typically, normal freshwater sources have a phosphorus concentration ranging from 0.005 to 0.05 mg/L.[363] In a global context, it can be observed that most wastewater treatment plants have a total phosphorus concentration of 1-4 mg/L in their effluent stream. [364] The European Union has set its limits at 1-2 mg/L, depending on the population served by the respective wastewater treatment plants.[351] In the USA, the limit is set at 1 mg/L.[365]

Ammonia

Ammonia is classified as a nitrogen-containing pollutant in wastewater. Excessive nitrogen, much like phosphorus, can lead to eutrophication of water bodies.[366] Even at concentrations below 1 mg/L, Ammonia can be toxic to fish and other aquatic organisms. Furthermore, ammonia contamination in water bodies can directly impact human health. Consumption of contaminated water or consumption of aquatic organisms from polluted waters can lead to adverse health effects in humans.[367] To remove ammonia from wastewater, there are physical, chemical and biological approaches.[368] The most widespread method for removing ammonia is through nitrification and optionally, denitrification, known as effective and cost-effective biological nitrogen removal. In this process, ammonia is converted into nitrite and then into nitrate, which are significantly less toxic. Subsequently, denitrification can convert nitrate into harmless nitrogen gas, which no longer poses toxic properties to the aquatic ecosystem.[369] The European Union sets the limit for total nitrogen in wastewater treatment plant effluent, which includes ammonia contaminants, at 10 mg/L to 15 mg/L. The number of people served by the respective facility is also crucial in determining this limit.[351]. Often, in wastewater analyses, ammonia is not directly measured; instead, the total amount of nitrogen present in the water is assessed. This parameter provides a good indication of how well the treatment processes in the facility are functioning. Therefore, for the sake of comparability, these parameters are measured using the TN metric.[370]

Technical Parameters

Scalability

One advantage of decentralized wastewater treatment systems is their ability to adapt to changing demographic conditions. These systems offer the possibility of upscaling.[371] However, the ability to adapt or to be modified strongly depends on the technology used.[372]

Energy Requirement

Energy consumption plays a significant role in water and wastewater management. In the context of conventional centralized wastewater treatment systems, they often account for more than 40 % [373] of a municipality's energy costs. Energy consumption is particularly problematic in developing countries. Decentralized wastewater treatment plants offer the possibility of significantly lower energy consumption.[374] The reduced energy consumption naturally leads to greater sustainability of the systems. By effectively utilizing the appropriate technology, decentralization represents a significant step towards achieving net-zero carbon emissions. [375]

HRT/ SRT

The HRT indicates the duration that wastewater remains in a reactor. This parameter specifies the time during which the contaminants in the water are exposed to the microorganisms within the reactor. In conventional wastewater treatment plants, this period ranges from 5-24 hours. [376] The HRT is directly related to the treatment efficiency and also depends on the specific technology used.[377] The SRT, on the other hand, indicates how long the sludge remains in the reactor. This has a significant impact on the microbial diversity in the reactor and thus on the pollutant removal efficiency. In most conventional wastewater treatment plants, this parameter ranges from 10 to 15 days. [378]

Sludge Management

This parameter aims to determine the most suitable type of sludge management for decentralized wastewater treatment in developing countries. The type of sludge management and therefore the treatment efficiency depends on the type of treatment system used.[379] Particular focus is on the disposal of the sludge. In developing countries, sludge disposal is often a recurring problem.[380]

Maintenance needs

Decentralized systems rely on a well-thought-out maintenance strategy to function properly. Training and regular inspections are particularly important in this regard.[381]. In most cases, the failure to establish decentralized wastewater systems is due to inadequate maintenance.[382]

Area

This parameter encompasses several factors, including topography, occupied space by the system, distance to receiving water bodies and the number of households to be served by the system.[383] For instance, topography influences energy consumption, while the number of households affected impacts treatment efficiency and the scale of the system.[384]

Economical Parameters

Initial Capital Cost

The initial capital costs represent a significant advantage that decentralized wastewater treatment facilities have over centralized wastewater treatment plants, as centralized facilities are inherently more cost-intensive due to their larger size alone.[385] The total implementation costs of the system depend on the technology employed, encompassing equipment, construction and installation expenses.[385]

O&M

The O&M costs, as the name suggests, pertain to the expenses associated with the operations of a facility. These costs can vary significantly depending on the utilization level.[386] Regarding wastewater facilities, operational costs include expenses such as energy, labor and chemicals.[387] It's also notable that operational costs vary depending on the technology employed.[387]

Lifecycle Cost

Lifecycle Costs (LCC) generally refer to the total ownership costs incurred over the entire lifespan of the wastewater treatment system.[388] In this analysis conventional LCC are considered, which primarily deals with the financial analysis, considering all stages in the lifecycle of the facility. Additionally, there is environmental LCC, closely linked to lifecycle analysis, focusing on environmental impacts in monetary terms. Furthermore, there are Societal LCC, which examine the societal welfare loss or gain from such a facility. However, for this analysis, only conventional LCC is considered, which includes maintenance and replacement costs, among others. [389]

C Expert Survey

For better clarity and verification of important parameters in the technical, economic and social analysis of decentralized wastewater systems, a questionnaire was distributed to experts from academic and professional backgrounds. This questionnaire can be viewed on the following page. A total of 49 responses were analyzed. The evaluation follows on the subsequent pages. It is important to note that for 'Section A: Wastewater Effluent Characteristics,' the parameters 'Pathogens,' 'pH Level,' and 'Heavy Metals' were not considered in the actual analysis. Instead, the parameter 'BOD/COD' was divided while maintaining the same weighting. The weighting of the excluded parameters was subsequently distributed empirically among the remaining parameters based on their respective weightings.

UC SANTA BARBARA
Bren School of Environmental
Science & Management

Expert Questionnaire Master Thesis Tim Dimmerling
Management Center Innsbruck, Austria
University of California Santa Barbara, USA

Assessing the Feasibility of Decentralized Wastewater Treatment Systems for Rural Communities in Developing Countries

Participant:

Name	*Profession*
Institution	*Date & Signature*

The survey aims to identify the key parameters deemed crucial for analyzing decentralized wastewater systems in rural areas of **developing countries**.

Please assign weights to the parameters listed below. This weighting is to be considered concerning the implementation of decentralized wastewater treatment in **developing countries**. A total of 100 points are to be distributed per section. (100 points = very important; 0 points = not important at all)

Section A: Wastewater Effluent Characteristics

Parameter	Weight
BOD/COD Reduction (=organic pollutant removal efficiency)	
TSS Reduction (=Reduction in total suspended solids (TSS) levels)	
Pathogens (=Effectiveness of the system in eliminating harmful pathogens to ensure public health protection)	
Phosphorus (=Effectiveness in removal of phosphorus compounds in the effluent)	
Ammonia (=Effectiveness in removal of ammonia)	
Fecal coliforms / Enterococcus (=Effectiveness in removal of fecal contamination)	
ph-Level (=Measurement of the acidity or alkalinity of the effluent)	
Heavy metals (=Effectiveness in removal of heavy metals)	
TOTAL	100

Remarks:

Section B: Economical Parameters

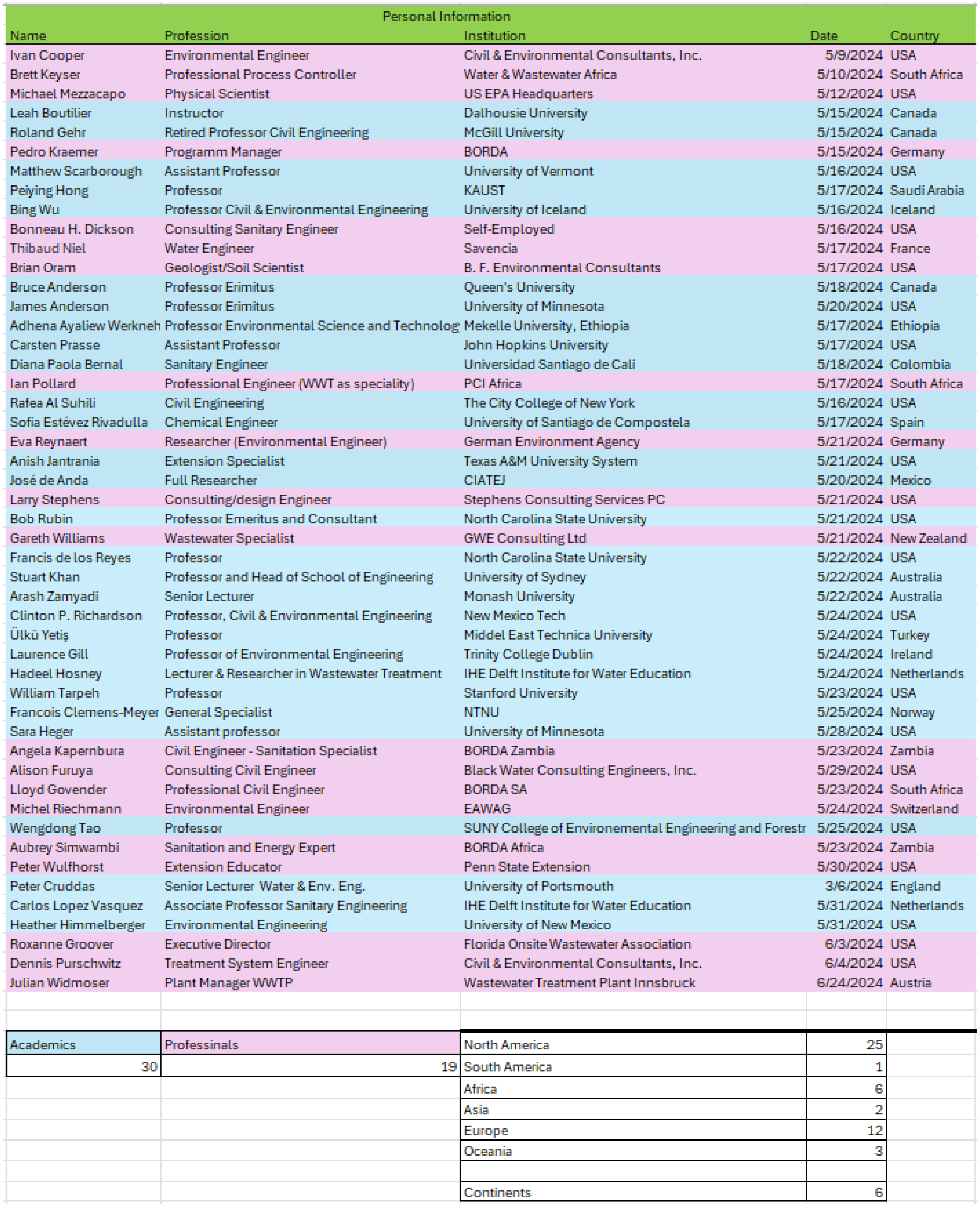
Parameter	Weight
Initial Capital Cost (=Total cost of implementing the system, including equipment, construction, and installation)	
Operational Cost (=Ongoing expenses associated with system operation, including energy, labor, and chemical costs)	
Lifecycle Cost (=Total cost of ownership over the expected lifespan of the system, including maintenance and replacement costs)	
Job Creation (=Potential for job creation within the local community)	
TOTAL	100

Remarks:

Section C: Technical Parameters

Parameter	Weight
Scalability (=Ability of the system to be expanded or modified)	
Energy Requirement (=Amount of energy needed to operate the system)	
Hydraulic Retention Time/ Sludge Retention Time	
Sludge Management (=Generation and characteristics of sludge produced during treatment, including volume, composition, and disposal options	
Maintenance needs (=Frequency and complexity of maintenance activities required to keep the system functioning optimally)	
Area (=Topography of the area under consideration and number of households covered)	
TOTAL	100

Remarks:



Personal Information				
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Ian Pollard	Professional Engineer (WWT as speciality)	PCI Africa	5/17/2024	South Africa
Rafea Al Suhili	Civil Engineering	The City College of New York	5/16/2024	USA
Sofia Estévez Rivadulla	Chemical Engineer	University of Santiago de Compostela	5/17/2024	Spain
Eva Reynaert	Researcher (Environmental Engineer)	German Environment Agency	5/21/2024	Germany
Anish Jantrania	Extension Specialist	Texas A&M University System	5/21/2024	USA
José de Anda	Full Researcher	CIATEJ	5/20/2024	Mexico
Larry Stephens	Consulting/design Engineer	Stephens Consulting Services PC	5/21/2024	USA
Bob Rubin	Professor Emeritus and Consultant	North Carolina State University	5/21/2024	USA
Gareth Williams	Wastewater Specialist	GWE Consulting Ltd	5/21/2024	New Zealand
Francis de los Reyes	Professor	North Carolina State University	5/22/2024	USA
Stuart Khan	Professor and Head of School of Engineering	University of Sydney	5/22/2024	Australia
Arash Zamyadi	Senior Lecturer	Monash University	5/22/2024	Australia
Clinton P. Richardson	Professor, Civil & Environmental Engineering	New Mexico Tech	5/24/2024	USA
Ülkü Yetiş	Professor	Middel East Technica University	5/24/2024	Turkey
Laurence Gill	Professor of Environmental Engineering	Trinity College Dublin	5/24/2024	Ireland
Hadeel Hosney	Lecturer & Researcher in Wastewater Treatment	IHE Delft Institute for Water Education	5/24/2024	Netherlands
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Francois Clemens-Meyer	General Specialist	NTNU	5/25/2024	Norway
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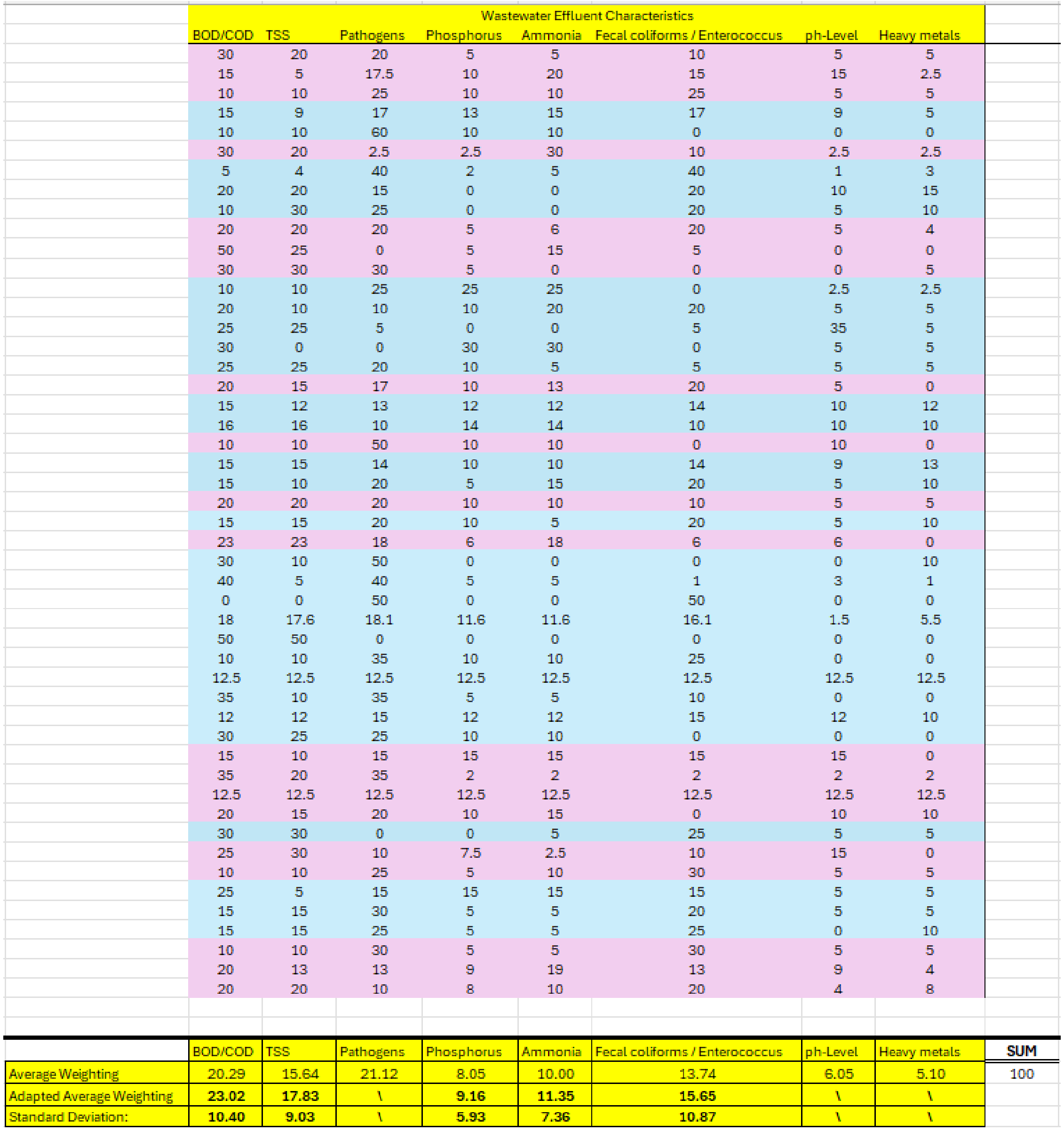
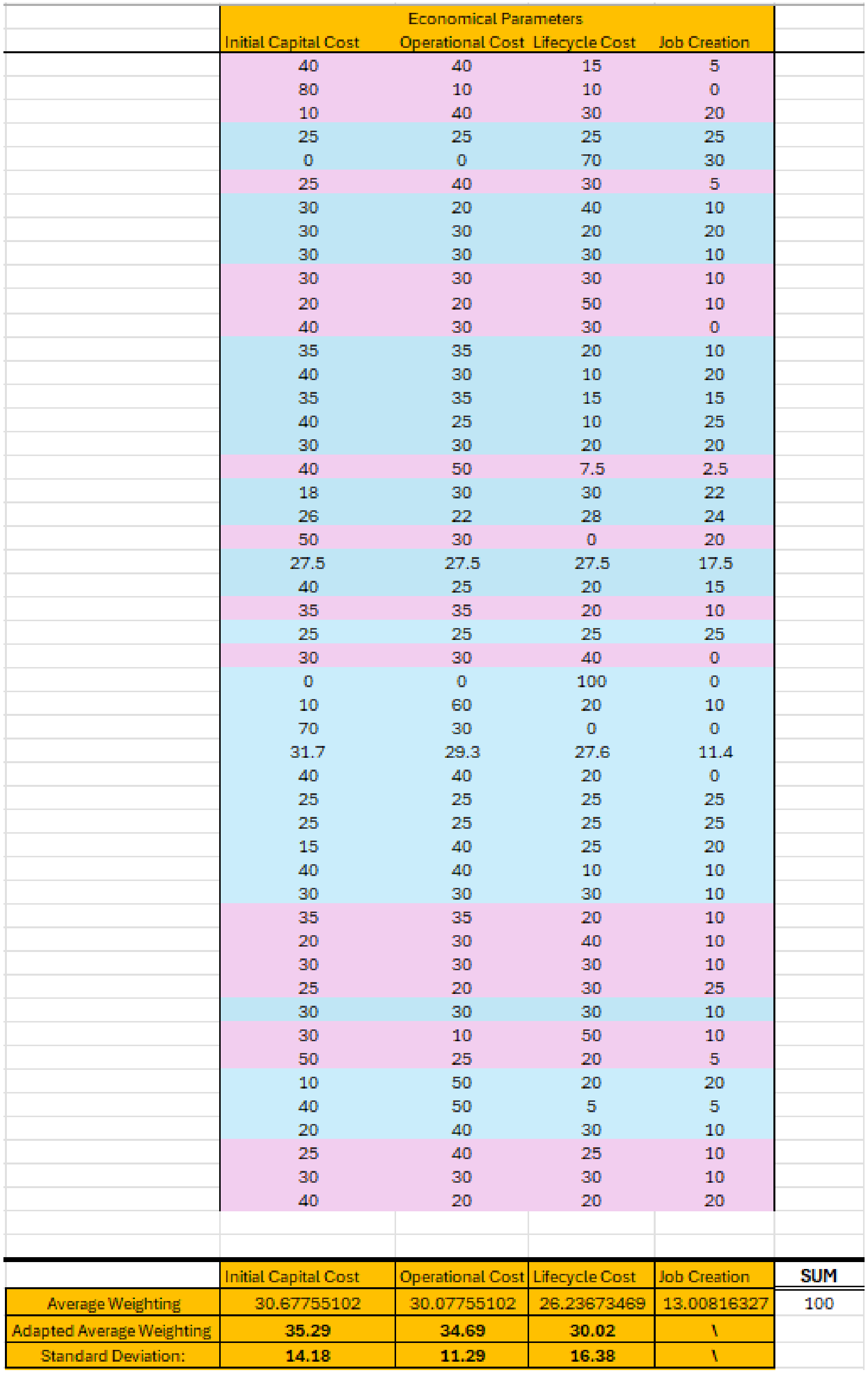
Academics	Professinals
30	19

North America	25
South America	1
Africa	6
Asia	2
Europe	12
Oceania	3
Continents	6



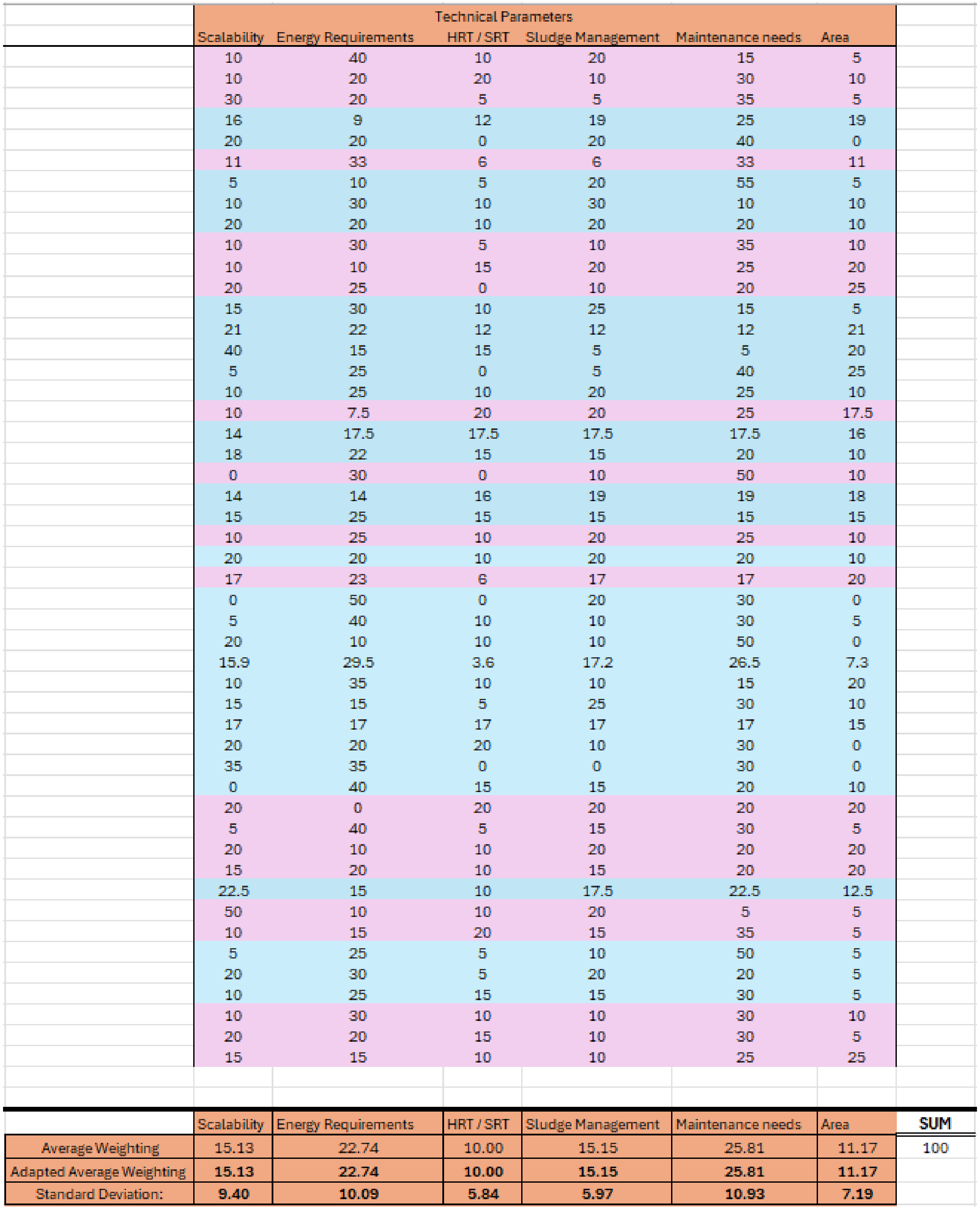
Wastewater Effluent Characteristics							
BOD/COD	TSS	Pathogens	Phosphorus	Ammonia	Fecal coliforms / Enterococcus	ph-Level	Heavy metals
30	20	20	5	5	10	5	5
15	5	17.5	10	20	15	15	2.5
10	10	25	10	10	25	5	5
15	9	17	13	15	17	9	5
10	10	60	10	10	0	0	0
30	20	2.5	2.5	30	10	2.5	2.5
5	4	40	2	5	40	1	3
20	20	15	0	0	20	10	15
10	30	25	0	0	20	5	10
20	20	20	5	6	20	5	4
50	25	0	5	15	5	0	0
30	30	30	5	0	0	0	5
10	10	25	25	25	0	2.5	2.5
20	10	10	10	20	20	5	5
25	25	5	0	0	5	35	5
30	0	0	30	30	0	5	5
25	25	20	10	5	5	5	5
20	15	17	10	13	20	5	0
15	12	13	12	12	14	10	12
16	16	10	14	14	10	10	10
10	10	50	10	10	0	10	0
15	15	14	10	10	14	9	13
15	10	20	5	15	20	5	10
20	20	20	10	10	10	5	5
15	15	20	10	5	20	5	10
23	23	18	6	18	6	6	0
30	10	50	0	0	0	0	10
40	5	40	5	5	1	3	1
0	0	50	0	0	50	0	0
18	17.6	18.1	11.6	11.6	16.1	1.5	5.5
50	50	0	0	0	0	0	0
10	10	35	10	10	25	0	0
12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
35	10	35	5	5	10	0	0
12	12	15	12	12	15	12	10
30	25	25	10	10	0	0	0
15	10	15	15	15	15	15	0
35	20	35	2	2	2	2	2
12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
20	15	20	10	15	0	10	10
30	30	0	0	5	25	5	5
25	30	10	7.5	2.5	10	15	0
10	10	25	5	10	30	5	5
25	5	15	15	15	15	5	5
15	15	30	5	5	20	5	5
15	15	25	5	5	25	0	10
10	10	30	5	5	30	5	5
20	13	13	9	19	13	9	4
20	20	10	8	10	20	4	8

	BOD/COD	TSS	Pathogens	Phosphorus	Ammonia	Fecal coliforms / Enterococcus	ph-Level	Heavy metals	**SUM**
Average Weighting	20.29	15.64	21.12	8.05	10.00	13.74	6.05	5.10	100
Adapted Average Weighting	**23.02**	**17.83**	\	**9.16**	**11.35**	**15.65**	\	\	
Standard Deviation:	**10.40**	**9.03**	\	**5.93**	**7.36**	**10.87**	\	\	



	Economical Parameters				
	Initial Capital Cost	Operational Cost	Lifecycle Cost	Job Creation	
	40	40	15	5	
	80	10	10	0	
	10	40	30	20	
	25	25	25	25	
	0	0	70	30	
	25	40	30	5	
	30	20	40	10	
	30	30	20	20	
	30	30	30	10	
	30	30	30	10	
	20	20	50	10	
	40	30	30	0	
	35	35	20	10	
	40	30	10	20	
	35	35	15	15	
	40	25	10	25	
	30	30	20	20	
	40	50	7.5	2.5	
	18	30	30	22	
	26	22	28	24	
	50	30	0	20	
	27.5	27.5	27.5	17.5	
	40	25	20	15	
	35	35	20	10	
	25	25	25	25	
	30	30	40	0	
	0	0	100	0	
	10	60	20	10	
	70	30	0	0	
	31.7	29.3	27.6	11.4	
	40	40	20	0	
	25	25	25	25	
	25	25	25	25	
	15	40	25	20	
	40	40	10	10	
	30	30	30	10	
	35	35	20	10	
	20	30	40	10	
	30	30	30	10	
	25	20	30	25	
	30	30	30	10	
	30	10	50	10	
	50	25	20	5	
	10	50	20	20	
	40	50	5	5	
	20	40	30	10	
	25	40	25	10	
	30	30	30	10	
	40	20	20	20	

	Initial Capital Cost	Operational Cost	Lifecycle Cost	Job Creation	**SUM**
Average Weighting	30.67755102	30.07755102	26.23673469	13.00816327	100
Adapted Average Weighting	**35.29**	**34.69**	**30.02**	****	
Standard Deviation:	**14.18**	**11.29**	**16.38**	****	



	Technical Parameters					
	Scalability	Energy Requirements	HRT / SRT	Sludge Management	Maintenance needs	Area
	10	40	10	20	15	5
	10	20	20	10	30	10
	30	20	5	5	35	5
	16	9	12	19	25	19
	20	20	0	20	40	0
	11	33	6	6	33	11
	5	10	5	20	55	5
	10	30	10	30	10	10
	20	20	10	20	20	10
	10	30	5	10	35	10
	10	10	15	20	25	20
	20	25	0	10	20	25
	15	30	10	25	15	5
	21	22	12	12	12	21
	40	15	15	5	5	20
	5	25	0	5	40	25
	10	25	10	20	25	10
	10	7.5	20	20	25	17.5
	14	17.5	17.5	17.5	17.5	16
	18	22	15	15	20	10
	0	30	0	10	50	10
	14	14	16	19	19	18
	15	25	15	15	15	15
	10	25	10	20	25	10
	20	20	10	20	20	10
	17	23	6	17	17	20
	0	50	0	20	30	0
	5	40	10	10	30	5
	20	10	10	10	50	0
	15.9	29.5	3.6	17.2	26.5	7.3
	10	35	10	10	15	20
	15	15	5	25	30	10
	17	17	17	17	17	15
	20	20	20	10	30	0
	35	35	0	0	30	0
	0	40	15	15	20	10
	20	0	20	20	20	20
	5	40	5	15	30	5
	20	10	10	20	20	20
	15	20	10	15	20	20
	22.5	15	10	17.5	22.5	12.5
	50	10	10	20	5	5
	10	15	20	15	35	5
	5	25	5	10	50	5
	20	30	5	20	20	5
	10	25	15	15	30	5
	10	30	10	10	30	10
	20	20	15	10	30	5
	15	15	10	10	25	25

	Scalability	Energy Requirements	HRT / SRT	Sludge Management	Maintenance needs	Area	**SUM**
Average Weighting	15.13	22.74	10.00	15.15	25.81	11.17	100
Adapted Average Weighting	**15.13**	**22.74**	**10.00**	**15.15**	**25.81**	**11.17**	
Standard Deviation:	**9.40**	**10.09**	**5.84**	**5.97**	**10.93**	**7.19**	

D Expert Interview BORDA

To clarify general and specific questions, an interview was conducted in a professional context with Nuth Makara, who serves as the Technical Coordinator for BORDA (Bremen Overseas Research and Development Association) in Cambodia. Nuth Makara specializes in the implementation of decentralized wastewater treatment systems. On the Sustainable Sanitation Alliance (SuSanA) website, BORDA is described as follows:

> *"BORDA e.V. (Bremen Overseas Research and Development Association) is a German non-governmental organization headquartered in Bremen, with a network of local partner organizations in over 20 countries worldwide. [...] Currently, BORDA focuses on decentralized sanitation solutions for underserved populations in peri-urban and urban areas across Africa, Asia and Latin America. To enhance access to improved sanitation, BORDA offers demand-oriented service packages, including decentralized wastewater management solutions (DEWATS) and decentralized solid waste management (DESWAM)."*
>
> (https://www.susana.org/en/community/partners/list/details/37, accessed 24.08.2024)

The results of the interview have been documented in writing and are presented on the following pages. The summary of the answers in the text boxes comes from the interviewee and has not been adjusted. Possible errors in spelling and grammar have therefore been retained.

UC SANTA BARBARA
Bren School of Environmental
Science & Management

Expert Interview Master Thesis Tim Dimmerling
Management Center Innsbruck, Austria
University of California Santa Barbara, USA

Assessing the Feasibility of Decentralized Wastewater Treatment Systems for Rural Communities in Developing Countries

Participant:

Name	*Profession*
Nuth Makara	Technical Coordinator
Institution	*Date & Signature*
BORDA Cambodia	23 Aug 2024

1. What are the primary challenges faced in implementing decentralized wastewater treatment systems (WWTS) in rural communities in developing countries?

1. Budget for construction

2. Household connection service

2. Why do decentralized wastewater treatment projects often fail in rural areas of developing countries? Can you provide specific examples or common pitfalls?

1. Lack of understanding of usefull of DEWATS system

2. Week O&M for sustainability

3. Stakeholder engargement and law enforcement

3. What are the most effective ways to generate funding for decentralized WWTS projects? Are there specific grants, international aid, or private sector investments that can be leveraged?

1. Reinforment the government law and follow to be treated wastewater before discharge to environment

2. Internation aid like BMZ and private sector who followed the government regulation and environment protection

4. How crucial is energy availability for the operation of decentralized WWTS? Would an energy-free system be more suitable for rural communities, and why?

Energy availability is crucial for decentralized WWTS, but energy-free systems, like those using gravity flow, can be more suitable for rural areas. These systems reduce costs and reliance on external energy, which is beneficial in regions with high energy costs or limited access, such as parts of rural Cambodia.

5. Are there successful examples of natural decentralized wastewater treatment systems being used in rural communities? If so, what are the key benefits and drawbacks of these systems?

Yes, there are successful examples of natural decentralized wastewater treatment systems, such as the Animal Farm DEWATS project.

Benefits:
- Treated wastewater can be safely discharged into nearby natural lakes, complying with environmental laws.
- Eliminates bad odors in the community.
- Promotes a clean environment around the farm and lake.

Drawbacks:
- High investment costs for setting up DEWATS.
- Requires technical skills for proper operation and maintenance.

6. What are the common maintenance and operational challenges for natural types of decentralized WWTS, and how can they be addressed?

Natural decentralized wastewater treatment systems often face several challenges:

1. They can get clogged with accumulated solids, so regular cleaning is needed.

2. Vegetation in systems like wetlands can overgrow and affect performance, requiring periodic trimming.

3. Pests and wildlife might interfere, which can be managed with barriers or deterrents.

4. Seasonal changes, like colder weather, can impact system efficiency, so it's important to design systems to handle these variations.

5. Additionally, these systems require trained personnel to operate and maintain them, so providing regular training and support is essential. Addressing these challenges involves consistent maintenance, monitoring, and proper training for those managing the systems.

7. How do you ensure user acceptance and proper use of decentralized WWTS in rural communities? Are there particular systems that are more user-friendly or culturally acceptable?

- Pre treatment system with low cost investment
- Septic tank with 2 or 3 chambers and 30% - 50% unsealed the bottom, ww will filtrated into the ground water body

1. Community engagement: Involve locals in planning to meet their needs.

2. Education and Training: Educate users on benefits and maintenance neccesity

3. Cultural Sensitivity: Choose systems that align with local practices.

4. User-Friendly Design: Use simple, low-cost systems like a septic tank with 2 or 3 chambers and 30% to 50% unsealed at the bottom, which allows wastewater to filter into the ground.

5. Feedback mechanisms: Provide ways for users to give feedback and report issues.

8. What opportunities exist for water reuse in the context of decentralized WWTS? How can treated wastewater be safely reused for agricultural or other purposes?

1. Agricultural use: Treated wastewater can be directed to irrigation canals and then pumped into rice fields, but not used directly on crops.

2. Gardening: Use treated wastewater for gardening by directing it to the soil around flowers, but avoid spraying it on top of the plants.

3. Farm use: For agricultural farms, treated wastewater can be applied a week after planting. It should be discontinued a week before harvesting and replaced with clean water to ensure that vegetables are free from contaminants.