THESIS

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Investigation Decentralised Wastewater Treatment Plant Installing Options in Vientiane, Laos.

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List of Abbreviations

ABR: Anaerobic Baffled Reactor

ADB: Asian Development Bank

AMR: Antimicrobial Resistance

BAST: Baffled Septic Tank

BASTAF: Baffled Septic Tank with Anaerobic Filter

BOD: Biochemical Oxygen Demand

BORDA: Bremen Overseas Research and Development Association

CBS: Community-Based Sanitation

CE: Circular Economy

CFU: Colony Forming Units

CLUES: Community-Led Urban Environmental Sanitation

COD: Chemical Oxygen Demand

CWs: Constructed Wetlands

DWR: Department of Water Resources

DHUP: Department of Housing and Urban Planning

DWWM: Decentralised Wastewater Management

ESCAP: Economic and Social Commission for Asia and the Pacific

FWs: Free Water Surface

GIZ: Gesellschaft für Internationale Zusammenarbeit

GLS: Gas-Liquid-Solid

HRT: Hydraulic Retention Time

HSF: Horizontal Subsurface Flow

JICA: Japan International Cooperation Agency

LDC: Least Developed Country

LIRE: Lao Institute for Renewable Energy

LMICs: Low- and Middle-Income Countries

MBR: Membrane Bioreactor

MBBR: Moving Bed Biofilm Reactor

MF: Microfiltration

MLSS: Mixed Liquor Suspended Solids

MOH: Ministry of Health

MONRE: Ministry of Natural Resources and Environment

MPWT: Ministry of Public Works and Transport

NAPPA: National Academy for Politics and Public Administration

N: Nitrogen

NHA: National Housing Authority

NGOs: Non-Governmental Organizations

NPSE: Nam Papa State Enterprise

O&M: Operation and Maintenance

OM: Organic Matter

P: Phosphorus

PCs: People’s Committees

PDR: People’s Democratic Republic

PGF: Planted Gravel Filter

R&D: Research and Development

ReSan: Real Estate Sanitation

SADCO: Sewerage and Drainage Company

S**BS**: Community-Based Sanitation

SBS-Lite: Community-Based Sanitation Lite

SBR: Sequencing Batch Reactor

SDGs: Sustainable Development Goals

SME: Small and Medium Enterprise

SS: Suspended Solids

SWOT: Strengths, Weaknesses, Opportunities, Threats

TSS: Total Suspended Solids

TWG: Technical Working Group

UASB: Upflow Anaerobic Sludge Blanket Reactor

UDAAS: Urban Development and Administration Authorities

UF: Ultrafiltration

UN: United Nations

UNESCAP: United Nations Economic and Social Commission for Asia and the Pacific

UWC: Urban Water Cycle

UV: Ultraviolet

VF: Vertical Flow

WHO: World Health Organisation

WSUC: Water Supply and Sanitation Users’ Committee

WSPs: Waste Stabilisation Ponds

WWTP: Wastewater Treatment Plant

1 Introduction

1.1 Introduction

Wastewater treatment is undoubtedly one of the fundamental aspect of urbanisation. With increasing urbanisation and population growth happening globally, the emphasis on an efficient and sustainable wastewater treatment system is increasingly becoming a priority. Conventionally, Centralised Wastewater Treatment plants are the preferred solution (Pasciucco et al., 2022) due to their ability to transport large amounts of wastewater. However, because centralised wastewater facilities are composed of high-tech equipment, the construction of these plants requires huge capital investments in infrastructure, extensive sewerage systems, and a highly qualified workforce with skills in operation and maintenance.

The establishment of a centralised wastewater facility in most developing or low-income countries is challenging given the budget limitations, limited technological access, and lack of technical expertise. This offers decentralised wastewater treatment systems (DEWATS) an alternative to centralised wastewater systems (Amoatey et al., 2011; Metcalf & Eddy, 2014; Pasciucco et al., 2022). DEWATS treated the wastewater close to the point of origin rather than relying on extensive sewer networks. This allows it to be more flexible, economically affordable, and offer scalable alternatives, thereby making it a viable option for countries and regions where a centralised system is not possible.

Decentralised wastewater treatment systems comprise of a wide array of technologies, ranging from simple, low-cost options like septic tanks and constructed wetlands to more advanced, high-performance systems such as membrane bioreactors (MBRS) and anaerobic baffled reactors (ABRs) (Bernal et al., 2021; Massoud et al., 2009; Tilley et al., 2014). Each technology, however, still has its own advantages and disadvantages. Therefore, it is necessary to choose a system suitable for the country’s circumstances. The selection of technology is based on multiple factors, such as wastewater characteristics, climate, resources, space availability, affordability, and the local regulations.

In the case of Vientiane, the capital city of Laos, wastewater management continues to be an ongoing problem. Like many others, the city is experiencing rapid urbanisation, which is resulting in increasing levels of wastewater production. Furthermore, because of a lack of a centralised wastewater system and an appointed government body, high volumes of wastewater generated from domestic, commercial and industrial sources are being released untreated into natural water bodies, causing environmental degradation and posing public health risks (Chanthavilay et al., 2017; Deevanhxay, 2022). These polluted water bodies deteriorate the quality of the water, exposing the locals to a higher risk of waterborne diseases to and causing ecological and environmental damage. If unaddressed, the situation will only worsen in the long run as urbanisation continues and the population grows, further straining the existing sanitation system.

The absence of a centralised wastewater treatment facility in Laos allows decentralised wastewater treatment system to be a suitable choice for wastewater management. While decentralised systems have been successfully used in many countries, few explorations has been done on their implementation in Laos (Baetings & Declan, 2010). This makes choosing a suitable wastewater treatment technology for Vientiane challenging, as most of the research regarding wastewater treatment technologies was done in countries with different environmental, economic, and regulatory circumstances. Moreover, decentralised systems themselves present unique challenges such as available funding, land and maintenance requirements, and varying levels of treatment effectiveness, which would require detailed evaluation before large-scale implementation action (Bright-Davies et al., 2015).

In conclusion this thesis aims to investigate several decentralised wastewater treatment systems and assess their feasibility in Vientiane, Laos. Additionally, this study will provide insights into which systems can best be implemented or improved in the city for better wastewater management by considering economic, technical, environmental, regulatory and social factors.

1.2 Objective

This study aims to:

1. Identify and analyse various decentralised wastewater treatment technologies suitable for Vientiane, Laos.
2. Assess the feasibility of implementing decentralised wastewater treatment systems in Vientiane, Laos, by examining economic, technical, environmental, regulatory, and social factors that influence their success and sustainability.
3. Recommend suitable decentralised wastewater treatment solutions for Vientiane, Laos, by comparing different technologies for implementing new systems and improving existing wastewater management practices.

2 Literature Review

2.1 Introduction to Wastewater Treatment

2.1.1 Overview of Wastewater

Wastewater, defined as water influenced by human activities (Sridhar et al., 2020), represents one of the most significant issues in urban and environmental management. Wastewater is a combination of complicated mixtures of organic and inorganic solids, nutrients, pathogens, and hazardous substances, with its composition varying depending on the source. The main goal of wastewater treatment is to eliminate these contaminants and allow the treated water, known as effluent, to be safely returned to nature (Metcalf & Eddy, 2014). Crini & Lichtfouse (2018) note that water contamination happens through various human activities, including domestic, industrial, and agricultural activities. It can be caused by both natural and anthropogenic factors, with a considerable emphasis on synthetic substance pollutants produced by chemical industries.

Wastewater treatment is therefore vital for (Amoatey et al., 2011):

- Reducing biodegradable organic substances in the environment.
- Lowering the nutrient content levels present in the environment.
- Removal and elimination of harmful pathogens.
- Recycling and reuse of water.

In 2023, the World Health Organisation (WHO) reported a volume of 267,55 billion m^3 of wastewater is produced annually across 231 nations (WHO, 2023) (see Fig.1). However, just 54.7% of them are treated safely, using secondary or higher treatment or meeting relevant wastewater effluent discharge regulations, supported by an estimate of roughly 58,502 wastewater treatment plants (WWTPs) worldwide (Saadatinavaz et al., 2024). While these statistics reflect an achievement in the way how wastewater is managed, they also uncover a huge deficiency as nearly half of the wastewater generated worldwide is left untreated.

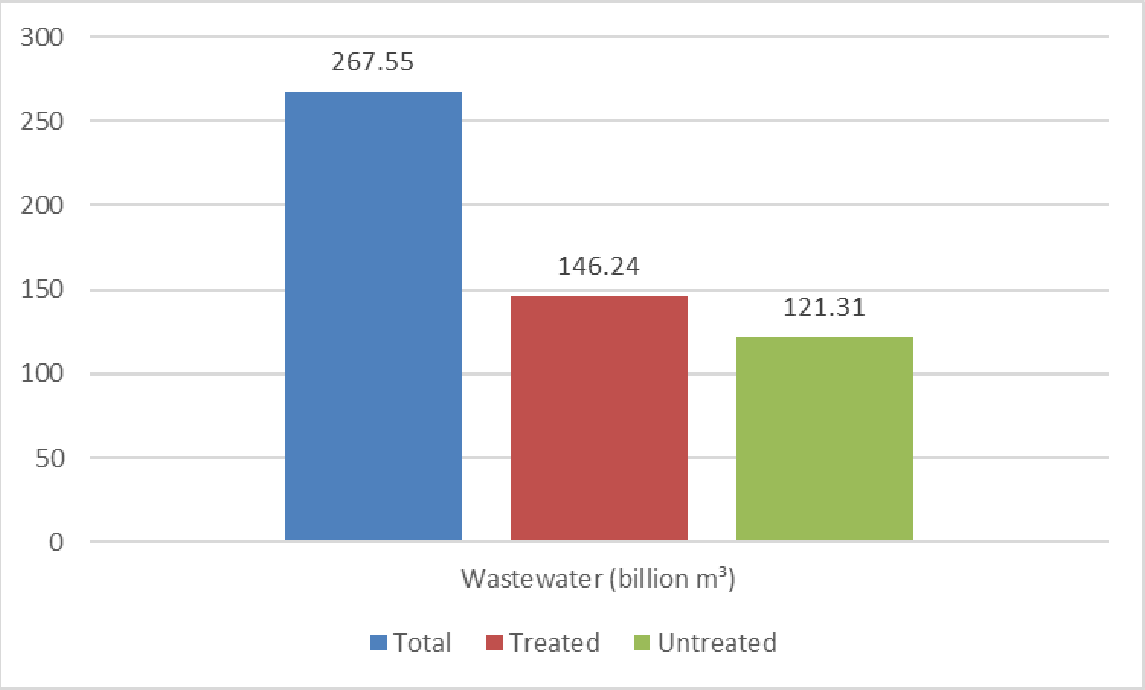


Figure 1: Bar chart of globally generated wastewater in 2023, including treated and untreated water (Source: own work based on data from WHO, 2023)

The connection between wastewater treatment, public health, environmental conservation, and urban sustainability is strong, as inefficient and inadequate wastewater treatment results in environmental pollution, health crises, and increasing economic impacts, particularly in countries that have lower and middle-income (WaterAid, 2019). Hence, wastewater management goes beyond treating and disposing waste; it is also important in meeting global development goals particularly those linked to sustainable development, resource efficiency, and climate resilience (Silva, 2023).

2.1.2 Characteristics of Wastewater

The elements found in wastewater are outlined in Table 1, taken from Etsuyankpa et al. (2024). The contribution of these components can vary considerably and each category requires targeted treatment technologies to mitigate its impact accordingly and effectively.

Pollutant/Contaminant	Description	Sources	Potential Impacts	Treatment Methods	References
Organic Matter	Decomposable materials like food waste and faecal matter	Domestic wastewater, Industrial effluents	Oxygen depletion, foul odour	Biological treatment, chemical oxidation	Olorunsola et al., 2024
Nutrients	Nitrogen, phosphorus, potassium compounds	Domestic, agriculture runoff	Eutrophication, algae blooms	Biological nutrient removal, chemical precipitation	Mathew et al., 2024
Heavy Metals	Lead, mercury, cadmium, chromium, arsenic	Industrial discharges, urban runoff	Toxicity, bioaccumulation	Precipitation, filtration, ion exchange	Mathew et al., 2024
Pathogens	Bacteria, viruses, parasites	Sewage, animal waste	Waterborne diseases	Disinfection (chlorination, UV treatment)	Adetunji et al., 2024
Suspended Solids	Soil, sediment, organic matter, debris	Urban runoff, erosion, industrial processes	Habitat degradation, reduced water quality	Sedimentaton, filtration, settling ponds	Inoberne et al., 2023

Table 1: Outline of wastewater characteristic (Source: Etsuyankpa et al., 2024)

2.1.2.1 Organic Matter

Organic matter (OM) that are dissolved in municipal wastewater is a mixture of recalcitrant substances, including drugs, disinfection by-products, personal care products, and metabolites (Vimala et al., 2020). Organic matter is measured using parameters like Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) and is one of the significant pollutants in wastewater management. BOD and COD parameters are vital water quality indicators as they determine the oxygen required for the biological and chemical decomposition of OM (Metcalf & Eddy, 2014).

2.1.2.2 Nutrients

Wastewater carries nutrients such as Nitrogen, Phosphorus, and Potassium which originates from sources such as human excreta, detergents and fertilisers. Whilst they are necessary to biological processes, excess of them may cause eutrophication. This phenomenon occurs when there is a high content of nutrients that facilitates algae growth and reduces oxygen levels, resulting in an ecological imbalance in water bodies, affecting the living organisms

(Witek-Krowiak et al., 2022). As such, the United States spends about $2.2 billion yearly on damaged mediation of eutrophication (Dodds et al., 2009).

Most WWTPs are engineered to eliminate nutrients from wastewater to mitigate their negative environmental impacts instead of recovering them. However over the past few years, a pivot in the research and policy towards nutrient recovery unfolded. This shift is based on acknowledgement that wastewater from industry and households as well as sludge are untapped sources for recovery of these nutrients and energy. Notably, the total amount of phosphorus in human waste can supply approximately 22% of the global phosphorus demand, which is essential for global food security (Kundu et al., 2022).

2.1.2.3 Metal Contamination/Containts

Industrial wastewater from processes such as manufacturing and mining can contain harmful metals like lead, mercury, cadmium, and others. These metals do not break down and therefore remain and build up in the environment with time. When released untreated, the accumulated metals are toxic to aquatic life and can disrupt biological processes hindering their development (Zhang et al., 2023). The metals can also bioaccumulate and bio-magnify in the food chain, aggregating to toxic levels in aquatic food consumed by humans. Chronic exposure to metals has been known to cause serious health issues (Oladimeji et al., 2024).

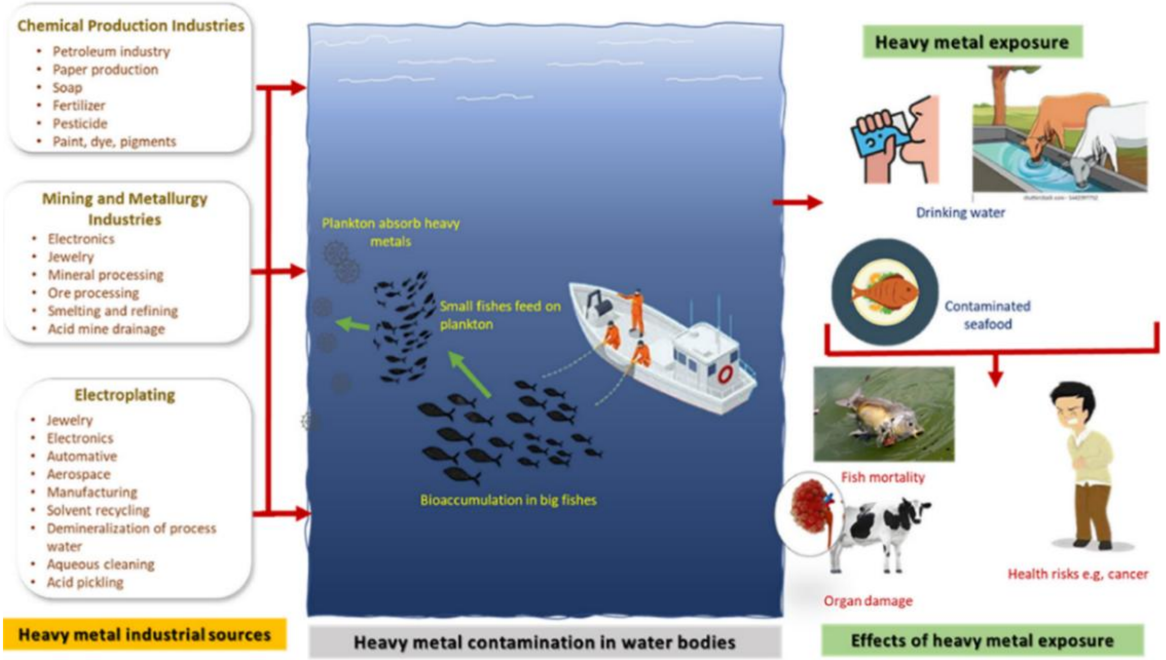


Figure 2: Industrial sources of heavy metals, and the impact of exposure on habitats
(Source: Oladimeji et al., 2024)

2.1.2.4 Pathogens

Every year, waterborne diseases cause an approximate of 2.2 million deaths worldwide, with 1.4 million of which being children (Ramírez-Castillo et al., 2015). The high mortality rate is largely attributed to the existence of diverse pathogenic microorganisms in wastewater, such as bacteria, viruses and parasites of human and animal origin. The presence of microorganisms raises considerable human health risks, as they are known to cause diseases like cholera, typhoid, dysentery, and gastroenteritis that can be transmissible. This is why; to protect public health, effective wastewater treatment is imperative to eliminate or inactivate the harmful microorganisms found in wastewater (Etsuyankpa et al., 2024).

2.1.2.5 Suspended Solids

Suspended solids (SS) in wastewater comprises of continuously suspended formations in water which includes soil, sediment, organic material, and any residues derived from erosion, runoff, industrial and human activity. The suspended sediments decreases the transparency of the water, restricts light penetration, and poses threats to aquatic organisms and its ecosystem (Etsuyankpa et al., 2024). When solid matter is suspended in wastewater, it is usually measured using a method known as total suspended solids or total suspended matter. This method is commonly used to investigate the constituents of suspended matter in drinking water or wastewater, which is typically organic-rich (Chan et al., 2008).

2.1.3 Sources of Wastewater

The sources of wastewater has a big influence on its composition, which can be categorised into three main groups (Amoatey et al., 2011): Stromwater Runoff, Industrial and Domestic wastewater (see Fig. 3).

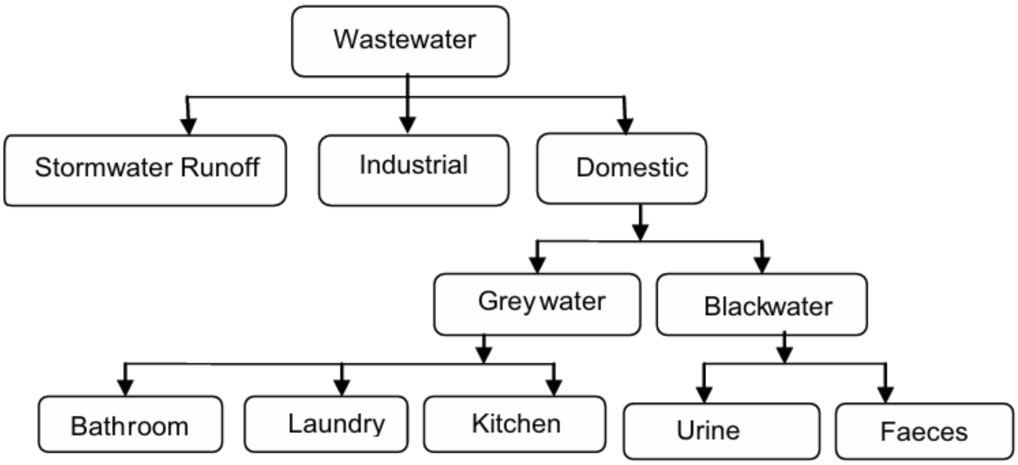


Figure 3: Types of Wastewater (Source: Amoatey et al., 2011)

2.1.3.1 Domestic Wastewater

The most significant contributor of municipal wastewater is domestic wastewater, which is mainly comprised of:

- ***Blackwater:*** Blackwater is discharge from sanitation facilities which contain high levels of organic, nitrogen and phosphorus content (Widyarani et al., 2022). Approximately 51% of COD, 91% of nitrogen (N), 78% of phosphorus (P), and a significant proportion of pathogenic microorganisms in domestic wastewater originates from blackwater (Terpstra, 1999). Blackwater represents a significant potential source of contamination for developing countries that lack proper sanitation facilities as the direct release of untreated blackwater results in safety issues for drinking water and food.
- ***Greywater:*** Greywater refers to wastewater produced from domestic and commercial operations, excluding sewage. It is sourced from domestic water units which consists of a combination of soap residues, detergents, organic waste, and nutrients (Spychała et al., 2019). Table 2, taken from (Shaikh & Ahammed, 2020), shows greywater sources and their constituents.

Greywater Source	**Constituents**
Bathroom	Shampoo, soap, toothpaste lint, traces of urine, body care products, hairs, skin, hair oil, body fats, hot water and sand/clay particles
Hand Basin	Toothpaste, soaps, body care products, shaving waste, hairs and skin cells
Kitchen	Dish washing detergents, oils and fats, food residue, hot water, raw meat washing, fruit and vegetable peels, tea or coffee, traces of food preseravtives, sand and clay particles
Laundry	Chemicals form detergents, oils, solvents, bleaches, paints, hot water, nonbiodegradable fibres from clothing

Table 2: Greywater sources and its constituents (Source: Shaikh & Ahammed, 2020)

2.1.3.2 Industrial Wastewater

Industrial effluent substantially varies in volume and quality depending on the industry. It may or may not be highly biodegradable and could contain compounds that make it resistant to treatment. Amongst these are organic synthetic compounds and heavy metals, the amount and quality of which can differ significantly between wastewater from developed and developing nations. The primary concern with industrial wastewater is the increasing volume of artificial compounds being released into the environment (Cisneros, 2011).

2.1.3.3 Stormwater Runoff

Stormwater or storm sewage is the water that flows from precipitation and is gathered through a series of pipes or open water channels. This runoff contains organic matter, suspended and dissolved solids, and many other substances that are collected as they move through the ground (Ambulkar & Nathanson, 2025). Sewage overflows, sediment erosion, and roadside litter are major polluters in stormwater runoff (Müller et al., 2020). The escalating volume of stormwater runoff from urban areas and the high levels of pollutants adversely affect urban watersheds on physical, chemical, and biological levels (Walsh et al., 2005). In addition, stormwater runoff adversely affects aquatic ecosystems, as it cause eutrophication, siltation, habitat loss, and long-term toxicity to the organisms (Kumar et al., 2024).

2.1.4 Global Importance of Wastewaster Treatment

Wastewater treatment is more than a technical task; it is a global necessity for improving human health, environmental stability, and sustainable development (Obaideen et al., 2022; Prüss-Ustün et al., 2014).

2.1.5.1 Public Health

Untreated wastewater plays a big role in the transmission of waterborne diseases, especially in low and middle-income countries (LMICs) (Prüss-Ustün et al., 2014). According to the World Health Organisation (WHO, 2023), every year, 1.4 million people die due to waterborne diseases, half of which are children under five years of age. These deaths correlate with microorganisms such as bacteria, viruses and protozoa, which are associated with human and animal wastes that are indirectly released into drinking water supplies or water bodies resulting in water outbreaks. Many microorganisms in wastewater can affect the human health by causing chronic diseases, as shown in Table 3 (Akpor & Muchie, 2011).

Another issue concerning conataminated wastewater is its ability to accelerate antimicrobial resistance (AMR) (Fouz et al., 2020). The presence of antibiotics and resistant bacteria in the wastewater stimulates the horizontal transmission of AMR genes, leading to severe crises worldwide in human health. The discharge of any antibiotic compounds into the waste system can be contribute for antibiotic-resistant microorganisms. For example, 75% of E. coli isolates in the Yamuna River in India are now resistant to a number of drugs (Singh et al., 2021), indicating the association between the spread of AMR and poor wastewater management.

A brief analysis of the following case study done by Paye et al. (2021) shows how a suitable sewage disposal process can postivielty affect public health. In Niger, cholera cases dropped in villages where all the locals were supplied with sources of clean drinking water compared to untreated sources. Similarly, in 2017, poor wastewater management in Lusaka, Zambia, led to a major cholera outbreak with 1,462 cases and 38 deaths. The results of the 220 tested water points showed that E. coli infections were found in 91% of the shallow wells and 34% of the boreholes (Nanzaluka et al., 2020). This reaffirms how proper water infrastructure is paramount to preventing disease transmission and shows how poor sanitary conditions/overburdened water infrastructure facilitate the spreading of disease.

Pathogen	Agent	Acute Effects	Chronic or Ultimate Effects
Bacteria	E.coli O157:H7 Legionella pneunomia Helicobacter pylori Vibrio chlolerae Campylobacter Yersinia Salmonella Cynobacter Leptosporosis	Diarrhea Pneumonia Gastritis Diarrhea Diarrhea Diarrhea Diarrhea Diarrhea Fever, Chills	Adults: death (thrombocytopenia) Children: death (kidney failure) Elderl, death Ulcers and stomach cancer Death Death: Guillian-Barre syndrome Reactive fever Reactive fever Potential fever Well's Disease
Parasites	Gardia lamblia Cryptosporidium Acanthamoeba	Diarrhea Diarrhea Eye infections	Lactose intolerance, Failure to thrive, Sever hypothyroidism Death in immunocompromised host
Viruses	Hepatitis viruses Adenoviruses Enchoviruses	Liver infection Eye infection Meningitis	Liver failure

Table 3: Acute and chronic health effects linked to microbial pathogens present in water (Source: Akpor & Muchie, 2011)

2.1.4.2 Environmental Sustainability

Currently, there is a push to achieve the globally adopted sustainable development goals (SDGs). Under its Global Sustainable Development Goals (see Fig.4), the United Nations aims to make sure that globally by 2030, everyone has equitable and universal access to safe and affordable drinking water. However, the latest UN statistics indicates that progress towards this goal is still slow in many countries. Thereafter, it is important to be aware of the potential risk posed by raw wastewater to the public health and the economy due to its environmental impacts on the receiving water bodies and the costs involved in its O&M. Sustainable water management goals depend highly on effective water treatment (Obaideen et al., 2022).

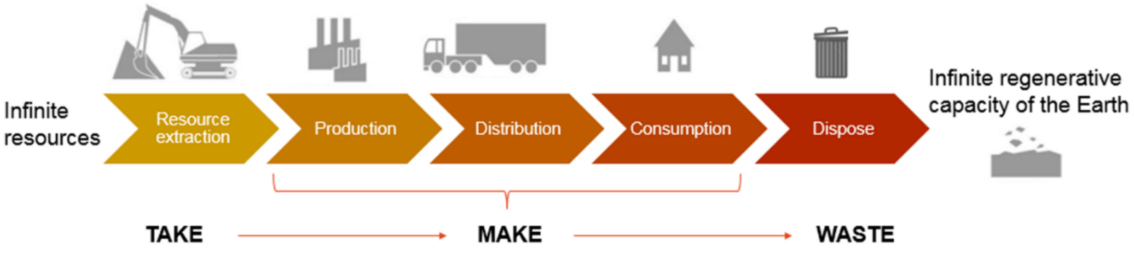
Figure 4: Sustainable Development Goals (SDGs) (Source: Obaideen et al., 2022)

Morelli (2011) defines environmental sustainability as “the ability to meet the needs of the present generation without compromising the ability of future generations to meet their own needs without compromising the health of ecosystems”. More specifically, it mirrors the balance, resilience and interdependence that allows human societies to meet their goals without surpassing the regenerative capacity of the supporting ecosystems or diminishing biodiversity through the process. Environmental quality has undoubtedly become a leading sustainable development goal in the forthcoming years (Khan et al., 2022).

2.1.4.3 Circular Economy and Resource Recovery

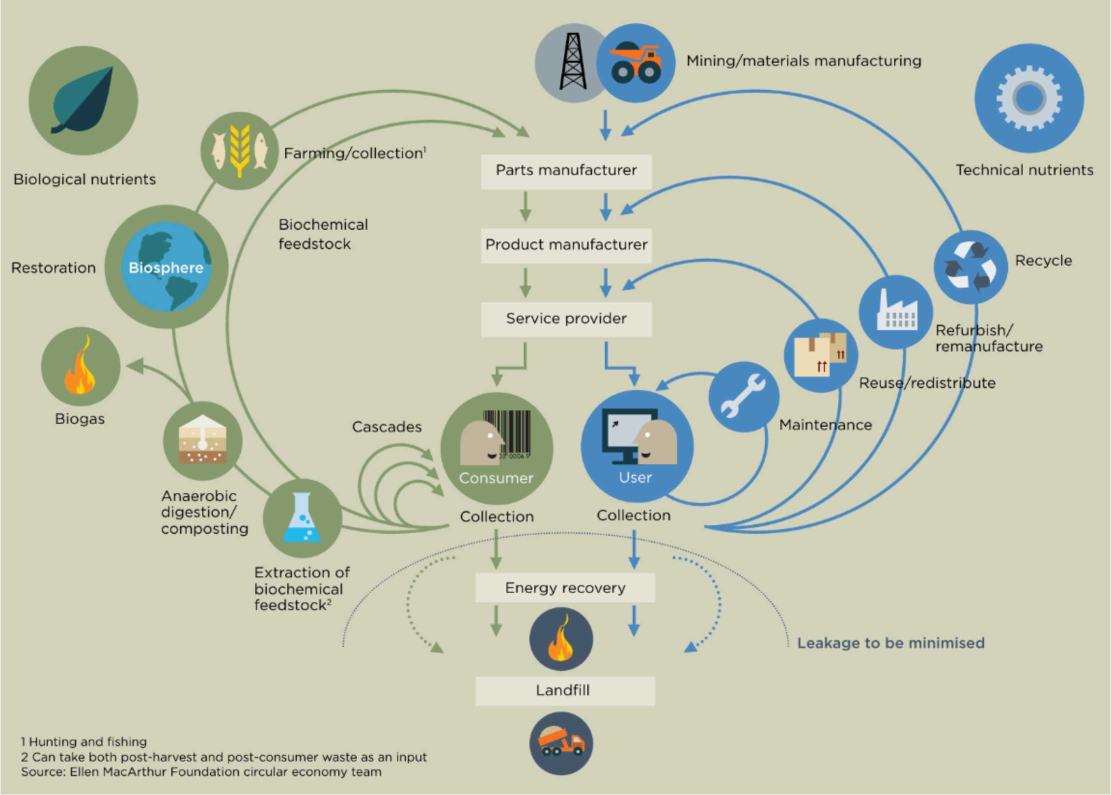
The circular economy (CE) (see Fig. 6) emerged as a transformative approach to sustainable resource management as an alternative to the traditional linear "take-make-waste" model (see Fig. 5). The circular economy aims to achieve the elimination of waste and pollution, extend the products and materials life span, and restore natures ecosystem. This shift towards circularity emphasises a closed-loop system, material recovery, and efficient use of resources to minimise environmental impacts and promote long-term sustainability (Chandratreya et al., 2024). It symbolises an approach that focuses on economic growth without needing to increase resource consumption, significantly reshaping production processes and consumer behaviours as well as redesigning industrial systems at a systemic level (Wautelet, 2018).

Figure 5: The linear economy - the "take-make-waste" approach of production



(Source: Wautelet, 2018)

According to Smol (2023), the regulatory aspects of the circular economy package are one of the significant issues that industrial and municipal players face today regarding environmental protection. This means that enterprises in different sectors, such as water and wastewater, must actively participate in the CE transition. Including CE concepts in the water and wastewater industry is fundamental as the approach addresses critical global problems concerning resource exhaustion, environmental degradation, and climate change (Kruopienė & Smol, 2024).



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input
Source: Ellen MacArthur Foundation circular economy team

Figure 6: The Circular Economy - an industrial system that is restorative by design
(Source: Ellen MacArthur Foundation, 2013)

Guerra-Rodríguez et al. (2020) emphasise that wastewater has to be considered a resource where the recovery of water, energy, and nutrients is achievable. This process helps to reuse the recovered resources in different applications, thus promoting sustainability and efficient use of resources. Similarly, Kehrein et al. (2020) addressed the need for technology innovations in applying circular economy concepts to wastewater management. Their research shows that new treatment processes can help recover valuable nutrients like phosphorus and nitrogen that can gain value in agricultural application. They also discussed the difficulty of incorporating the technologies into the current wastewater treatment plants and what it would cost to do so (Kruopienė & Smol, 2024).

Building further on this concept, Gherghel et al. (2019) critically discussed the CE prospect within urban water systems and how water reuse and energy recovery practices can substantially contribute to reducing the environmental footprints of such systems. On top of that, they emphasised the role of enabling policies, technology advancement and public sensitisation in addressing the barriers to the large-scale implementation of the intervention. Lastly, by drawing on the concepts of CE, Smol et al. (2020) proposed a combined approach of the "6Rs: Reduce, Reclaim, Reuse, Recycle, Recover, and Rethink" (see Fig. 7). This framework facilitates efficient waste treatment, generation minimisation and resource extraction maximisation, thereby promoting sustainable water management. (Kruopienė & Smol, 2024).

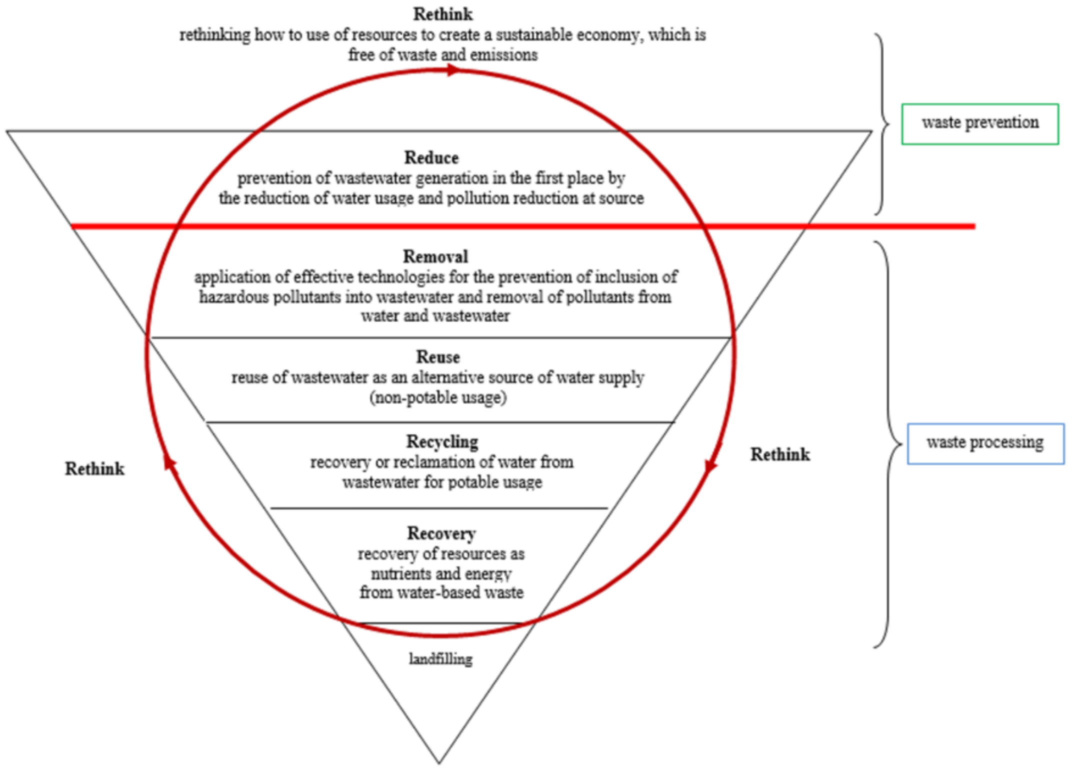


Figure 7: The Circular Economy model framework in the water and wastewater sector (Source: Smol et al., 2020)

2.1.5.4 Alignment with Global Governance Frameworks

Wastewater management faces countless challenges. Collective societal measures to protect public health and conserve water resources is therefore a must. To make this possible, an effective governance is essential and involves legal, institutional, financial, economic, and social and cultural factors. According to the established regualtions, both individuals and institutions must act in the public interest and at the same time satisfy their own needs stimultaneously. Therefore, policy outcomes depend primarily on how these responsibilities are carried out at all levels, considering the costs (Hendry et al., 2017).

Table 4 summarises the governance roles associated with wastewater management, encompassing the creation of policies and legislation, conducting research and improving capacity development, including primary and secondary roles, and the collaboration efforts required for effective execution. Most roles, however, focus more on centralised approaches, where local and alternative sanitation and drainage systems require further supporting parties. In the case of low-income or remote areas, capable leaders for policy development and implementation are often lacking. This means that support and attention from policy-makers are required (Hendry et al., 2017).

Functions and Actors	Legislator/Politician/Policy-Maker	Regulators (enivironment, health, economic)	System Owner (city, ministry, basin agency)	Operator/Service Provider	Academia/Policy Institutes/Think Tanks	Producer/Consumer (agriculture, industry, households)	Civil Society, NGOs
Law-making	Define and adopt laws through inclusive consultative process	Share expectations as to governance role	Share expectations as to governance role	Share expectations as to governace role	Provide input for law design	Share expectations as to governance role through participation	Share civil society opinions as to governance processes to provide input into law design
Policy-making	Define and adopt policies to implement the law through inclusive consultative processes	Share information on current situatuion and policy preferences	Share information on current situation and policy preferences	Share information on current situation and policy preferences	Share evidence-based input for policy design	Share information on current situation and policy preferences	Share information on current situation and policy preferences
Planning, coordination and budgeting	Define modalities for planning coordination and budgeting	Share preferences through constructive participation	Lead consultations, define standards for service delivery, allocate and disburse budget	Share preferences through contructive participation	Share preferences through constructive participation	Share preferences through constructive participation	Share preferences through constructive participation
Financing wastewater management	Decide on subsidies and modalilites for financing	Regulate tariffs and service quality	Strategic financial planning, decisions on tariffs	Collect information on investment needs and supply costs	May provide information and advice	Pay tariffs and provide information on willingess and abililty to pay	Monitor financial accountability; raise awareness regarding the cost of services
Wastewater infrastructure developement and operation of wastewater services and facilities	Guide standards/regulations for construction and operation of infrastructure	Regulate tariffs and service quality	Coordiante spatial planning, siting/zoning decisions; prepare call for tenders, depending on the type of services/goods	Construction; maintenance; operation; billing; revenue collection, customer relations	Can monitor processes and act as a social witness in integrity pacts (corruption prevention tool)	Should be involved in issues like siting/zoning decisions, acceptability, etc	Can monitor processes and act as social witness in integruty pacts (corruption prevention tool)
Regulation – monitoring and enforcement	Define regulatory framework	Implementation of regulatory framework (including collection of information fromm service providers and permit holders, ensuring compliance, inspections, etc.)	Report suspect actions	Provide information on request	Conduct long-term studies and analyse processes	Industry to provide information on request	Report suspect actions to law enforcement authorities

Redress mechanisms (including judiciary)	Define competant authorities for redress	Accountable or party to compliant	Accountable or party to complaint	Accountable or party to complaint	Expert (amicus curiae)	Accountable or party to complaint	Party to complaint and/or expert (amicus curiae)
Compliance and pollution prevention	Develop incentives for prevention and disincentives for pollution	Implement incentives (including monitoring and advocacy for pollution prevention and water-use efficieny)	Support implementation	Comply with regulations; improve technology and organisation	Support implementation	Implement cleaner production and reuse technology; correct waste disposal; improve agriculture practices	Advocacy for pollution prevention and water use efficiency
Advocacy and communications	Define policy goals and defend space for communication	Advocacy for pollution prevention and water-use efficiency)	Awareness-raising and information to the public, solicit compliant behaviours from industry and households	Advocacy for pollution prevention and water use efficiency	Long-term studies and analysis of processes; awareness-raising	Dialogue with partners and general audience about policy messages	Raise awareness
Capacity development	Defining policy goals for sector; and develop capacitites	Monitor capacities and incentivise developement	Support developement	Skills developemnt and professionalisation of wastewater management and services delivery	Provide training and education		
Research and innovation	Highlight research needs, ensure support to research and developemnt (R&D)	Highlight research needs; incentivise R&D	Highlight research needs; guides and engage in R&D	Participate in research, developement and test new technology solutions	Research on contaminants, pollution loads, ecological functions, system interactions, human behaviour	Participate in research, developemnt and testing of new technologu solutions	Highlight research needs, participate in research

Table 4: Actors, roles and functions to govern wastewater *Shading refers to level of responsibility: darkest = leading, lightest = least involved (Source: Hendry et al., 2017)

2.2. Overview of Wastewater Management Systems

Smol et al. (2020) describe wastewater management as “part of water and municipal management because it covers issues such as collective water supply systems, sewage disposal and treatment, individual water supply and wastewater systems, sewage sludge disposal, rainwater and land drainage and appropriate treatment”. Wastewater treatment involves multiple procedures to remove the impurities before the release or repurposing. These procedures include physical, chemical, and biological unit processes that work together to reduce the quantity of various pollutants in wastewater to safe levels. These unit procedures are applied at multiple treatment stages, including preliminary, primary, secondary, and tertiary treatment (see Fig. 8) (Donald et al., 2022).

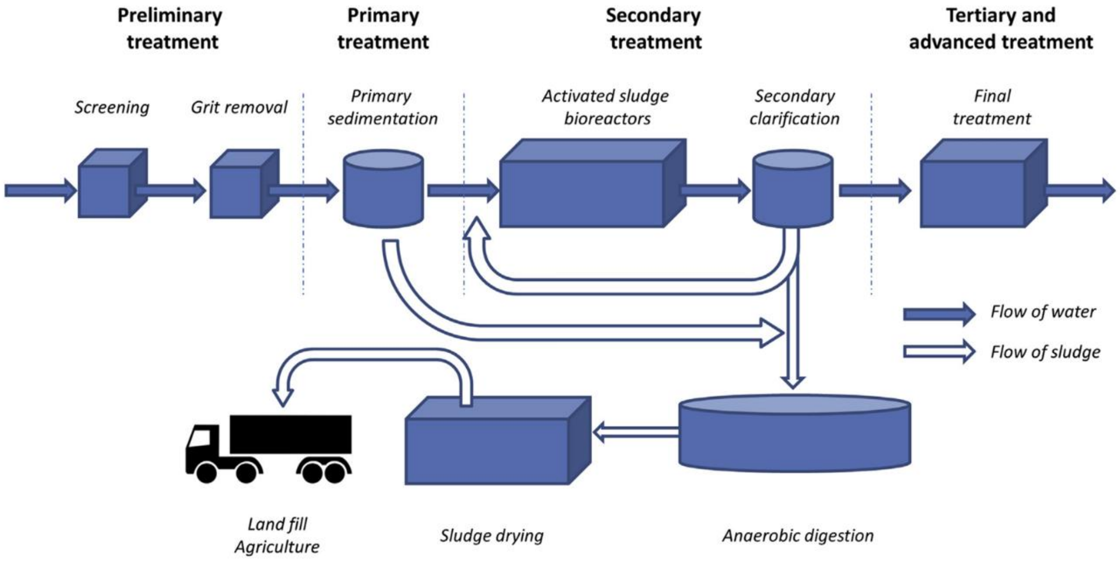


Figure 8: Wastewater Treatment Stages (Source: Donald et al. 2022)

Amoatey et al. (2011) breifly describes each treatment stages as follows:

1. Preliminary treatment

The preliminary treatment stage is the first phase, which removes coarse suspended particles and grits. Screening and grit chambers can remove these, enhancing the operation and maintenance of the following treatment units. (Amoatey et al., 2011)

2. Primary treatment

The primary treatment stage removes settleable organic and inorganic solids by sedimentation and floating materials such as scum through skimming. At this stage, up to 50% of BOD, 70% of SS, and 65% of oil and grease can be removed, as well as organic nitrogen, phosphorus, and heavy metals. However, during this stage, suspended and dissolved particles are not removed. Effluents from primary sedimentation units are referred to as primary effluent (Amoatey et al., 2011).

3. Secondary treatment

The third phase, or the secondary treatment stage, is an additional treatment process of the primary effluent to remove remaining organic materials and suspended solids. This stage uses aerobic biological processes to decompose biodegradable dissolved and colloidal organic matter. The organic matter is removed alongside the nitrogen compounds, phosphorus compounds, and pathogenic microorganisms. Nitrogen and phosphorus compounds, pathogenic microorganisms, and organic matter are removed during this process. Treatment can also be achieved using mechanical processes, such as trickling filters, activated sludge processes and rotating biological contractors or non-mechanically, such as anaerobic treatment, oxidation ditches, stabilization ponds, etc (Amoatey et al., 2011).

4. Tertiary treatment

Tertiary or advanced treatment is the last phase, removing specific wastewater compounds that the secondary treatment couldn't. The tertiary treatment phase eliminates a considerable amount of nitrogen, phosphorus, heavy metals, biodegradable organics, bacteria and viruses. At this stage, disinfection can be done by injecting chlorine, ozone, and ultraviolet (UV) irradiation into the water, ensuring it meets international standards for agricultural and urban reuse (Amoatey et al., 2011).

One of the important decisions at the planning stage for wastewater collection and treatment infrastructure is the degree of centralisation. Choosing the most suitable wastewater management strategy is difficult, as several considerations need to be considered, which are quite hard to evaluate. Two wastewater system strategies are recognised: centralised or decentralised management systems. In centralised systems, wastewater is transported to a WWTP that is located outside the served area, whereas in decentralised systems, wastewater is treated near or at the source itself (Pasciucco et al., 2022). Centralised wastewater systems are used more in developed countries, while decentralised solutions are more common in developing countries. That said, decentralised approaches are capable of meeting the conventional requirements of centralised treatment facilities, offering additional benefits such as reducing potential contamination of residual effluent and minimising the disruption to ecosystems by effectively eliminating micropollutants, which include metals, pharmaceuticals, and cosmetic products (Libralato et al., 2012).

In the 1990s, decentralised wastewater treatment was recognised and became a cost-effective solution for low- and middle-income areas (ADB, 2021). In Southeast Asia, the Bremen Overseas Research and Development Association (BORDA) promoted the strategy under the term DEWATS or Decentralised Wastewater Treatment Systems. Today, it is recognised by both international agencies and NGOs as an appropriate wastewater treatment method. Despite limited financial, human, and institutional resources, it can perform well with high wastewater treatment coverage. DEWATS is flexible, efficient, and cost-effective and can treat both household and industrial wastewater. More importantly, it serves as a good subtitute to the conventional centralised system for treating and managing wastewater (ADB, 2021). BORDA's incentive is not to promote any specific technologies but to propose a different perspective of handling wastewater, considering the rapid urbanisation happening in many cities worldwide (BORDA, 2017).

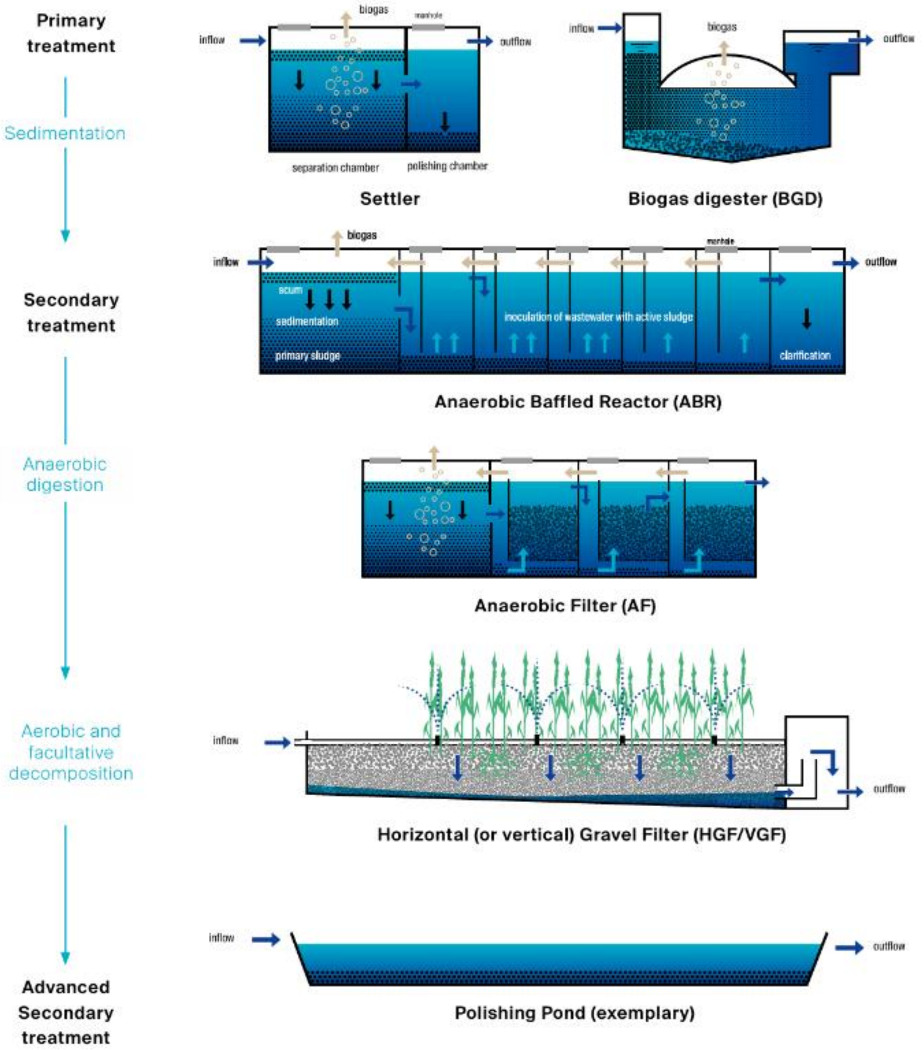


Figure 9: An example of treatment modules fulfilling the DEWATS principles (Source: BORDA, 2017)

With its nature-inspired technology, DEWATS utilises the physical processes of nature together with the aerobic and anaerobic activities of microorganisms that happens in wastewater. The principle of the system is rooted in decentralisation, simplicity, and recycling of the treated water. Its simplicity is realised through on-site treatment that does not rely on chemicals, electrochemical devices, or energy consumption. It requires minimal maintenance as managemnt can be performed by service providers or by on-site personnel who are supervised and properly trained. DEWATS facilitates sustainable wastewater management at a community level, accommodating systems serving single households or shared facilities that support approximately 2,500 households (equivalent to 1,000 m^3 per day) and public or commercial establishments (ADB, 2021).

The main benefits of DEWATS include (ADB, 2021):

- Suitable for diverse local conditions and is adaptable for multiple applications.
- Can be constructed using local materials and labour.
- Offers dependable and effective treatment for both domestic and industrial wastewater.
- Can be designed and built in a short timeframe.
- Features a reliable and durable construction design.
- Involves low operating and maintenance costs.
- Requires minimal resources for operation and maintenance.

2.3. Decentralised Wastewater Treatment Technologies

Decentralised wastewater treatment systems includes a range of technologies, ranging from simple, low-cost technologies to advanced high-efficiency systems. The selection of technology depends on the wastewater characteristics, climate, available resources, and regulatory drivers (Bernal et al., 2021).

2.3.1 Basic Systems

On-site sanitation is designed to manage or treat faeces or sewage where it is sourced rather than transporting it elsewhere. This decentralised sanitation system allows the collection, storage, and, in limited circumstances, treatment of human waste at the place of usage without using a centralised sewerage system. Such systems are crucial in many developing countries where modern sewer infrastructure is often lacking. This challenge is especially pronounced in rural areas, peri-urban settlements, and informal urban communities, where traditional wastewater management solutions may be impractical or inaccessible (Affam & Ezechi, 2021).

2.3.1.1 Pit Latrines

Pit latrines are an example of how to treat waste in situ. They are essentially holes in the ground, sometimes unlined or lined with a substance meant to contain human waste. The load of the pit is designed to hold excreta and materials for the anal cleansing for a specific number of users over a fixed period. An accumulated pit of waste is considered full when the height of waste accumulated is approximately below the surface above 0.5 to 1.0 metres. Depending on how well they are constructed and used, pit toilets may work well anywhere from 10 to 30 years, but many are only used up to 5 years before emptying or closing off. When the pit reaches its limit, its contents, including faecal sludge, can be removed, or the top 0.5 metres to 1.0 metres of the space can be backfilled with soil. In these cases, the pit will be removed from service, and the top parts, such as the concrete pad and privacy screens, can be disassembled and relocated to a new pit (Orner et al., 2019).

2.3.1.2 Septic Tanks

Septic tanks or settlers treat wastewater with a highly settleable solid content, such as domestic sewage. They are closed, often prefabricated tanks where solids settle after sedimentation. Retention takes about one day, allowing for anaerobic processing of the sludge, thereby reducing its volume. The treatment process is fully passive and only needs occasional inspection, cleaning of the effluent filter, and sludge removal for maintenance (Technologien & Wirtschafts, 2001).

Adequate hydraulic residence time is required to separate solids from liquids, which is critical for the effectiveness of the treatment. Tanks are commonly designed with two or three chambers to enhance this separation. Less dense materials, including greases, fat and oil, skims at the surface and forms scum layer. Denser solids, in contrast, sink to the bottom, where sludge forms. This process creates a middle section of moderate clarified wastewater that flows to the next chamber or treatment outlet. The outlet from the last chamber delivers treated effluent to a subsurface drain field or other treatment systems (Adegoke & Stenstrom, 2019).

Indigenous bacteria in the tank digest some of the solids by anaerobically breaking it down; solids accumulate as sludge and scum layers. Any scum and sludge that does not get fully degraded will stay until the septic tank is pumped out. Without proper maintenance, these layers can become pollution hotspots (Richards et al., 2016). The septic tank is widely used in remote or low-income urban areas, for single or group households, or at sites with unsatisfactory conditions for sewer systems (Jiménez & Wang, 2006).

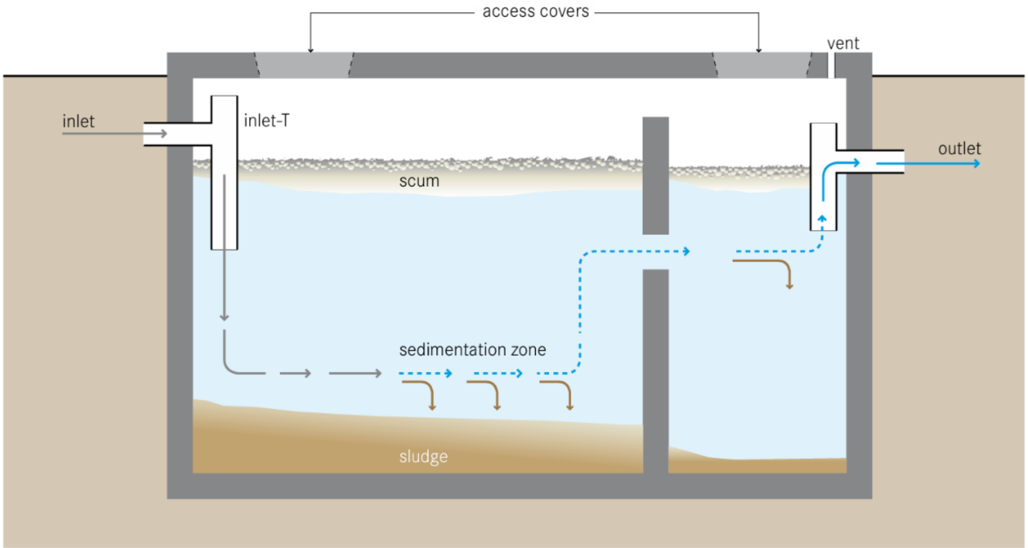


Figure 10: A septic tank consists of three distinct layers: the top layer of scum, a middle layer of clear water, and a bottom layer of sludge (Source Tilley et al., 2014)

2.3.1.3 Anaerobic Filter

As Tilley et al. (2014) describes the anaerobic filter as a “fixed-bed bioreactor containing one or more filtration chambers arranged in series”. It effectively treats and allows dissolved and non-settleable solids to be in close contact with high concentrations of rapidly multiplying active bacteria, which can digest the concentration of organic matter within a short retention time. These bacteria are mostly remain stagnant and will attach itself to fixed surfaces such as reactor walls, filter media, gravel, stones, cinder, or specially designed plastic parts that offer additional surface areas available for thr bacteria to colonise. As a result, the fresh wastewater interacts more effectively with the active bacteria, accelerating the digestion process as the available surface area for bacterial growth increases (Technologien & Wirtschafts, 2001).

Pre-treatment and primary treatment is needed to remove large solids and debris to avoid the filter from clogging up. Most of the settleable solids are removed from wastewater in a sedimentation chamber before reaching the anaerobic filter. Typically, these filters operate in an up-flow design mode to limit the risk of the fixed biomass being washed out. The water level must cover the filter media by at least 0.3 metres to ensure that there is an even flow regime. Key design parameters include the hydraulic retention time (HRT), of which the recommended HRT is 12 to 36 hours. The connection between the chambers can arranged with vertical pipes or baffles, and all chambers should be accessible for maintenance. Furthermore, the tank should have ventilation to allow for the safe escape of odorous and harmful gases (Tilley et al., 2014).

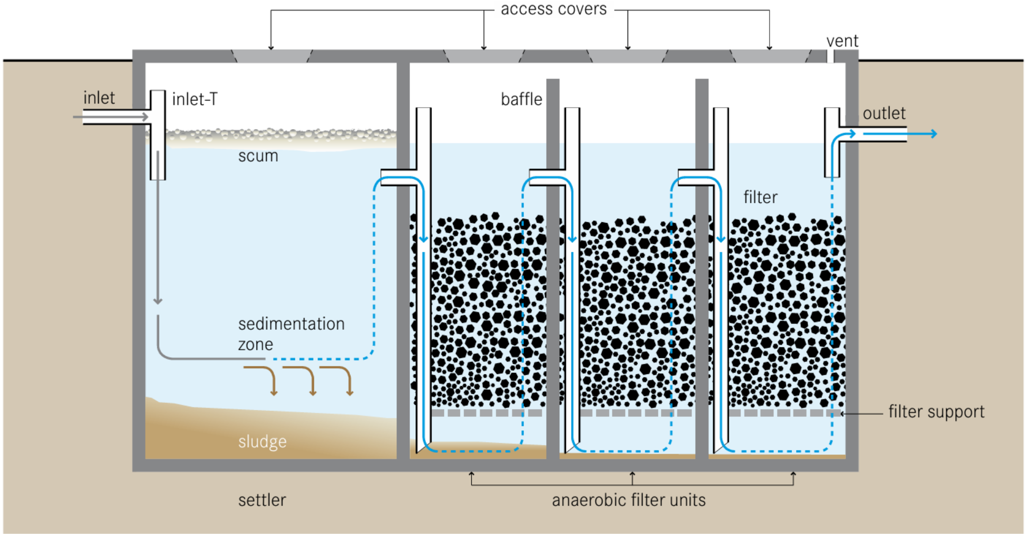


Figure 11: Schematic of an anaerobic filter system (Source: Tilley et al., 2014)

2.3.2 Nature-Based Treatment Solutions

According to Brix (1995), Nature-Based Solutions have historically supported wastewater treatment. The ancient Egyptians and the Chinese both used wetlands for wastewater disposal. It involved direct discharge of wastewater into surface water bodies, where biosolids and nutrients settled and created natural wetlands followed by the growth of vegetation. As a result, this process enabled the natural treatment of wastewater while maintaining the ecosystem even at low discharge loads.

2.3.2.1 Constructed Wetlands

Constructed wetlands (CWs) are engineered systems that were designed to imitate the natural purification process of wetlands (Hadidi, 2021). Several corresponding mechanisms predominantly determine the effectiveness of CWs in removing pollutants. Under the action of gravity, suspended solids are allowed to settle, and pollutants are trapped in the matrix of the substrates through the processes of filtration and adsorption. Microbial degradation reuses organic matter and facilitates nutrient transformation, particularly via the nitrification-denitrification process. Chemical precipitation also precipitates huge loads of insoluble compounds that settle out of the water column, and nutrient uptake by plants also removes nitrogen and phosphorus. These natural mechanisms allow CWs to eliminate organic matter, nutrients, heavy metals, and pathogens (Abdel-Shafy & Mansour, 2022).

The types of CWs are categorised according to their water flow patterns and the types of vegetation present. Free Water Surface (FWS) wetlands resemble natural marshes, with the wastewater flowing above the substrate through vertical emergent macro-vegetation. Sedimentation and pathogen removal are particularly effective with this system. On the other hand, in a Horizontal Subsurface Flow (HSF) wetlands system, wastewater moves horizontally under the wetland surface through a wide porous media, minimising odour and mosquito breeding and efficiently removing high OM and SS. In the case of high plant coverage in Vertical Flow (VF) wetlands, oxygen transfer is enhanced due to permeation of wastewater through the substrate, encouraging nitrification processes (Stefanakis et al., 2014).

2.3.2.2 Waste Stabilisation Ponds

Waste Stabilisation Ponds (WSPs) are large and shallow ponds that treat wastewater by using natural biological mechanisms in a manner that depends on algae and bacteria. Anaerobic Ponds are deep ponds and are mainly used to remove high organic loading, BOD, through sedimentation and anaerobic digestion (Kayombo et al., 2004). They operate without needing oxygen, using anaerobic bacteria to break down organic matter into methane and carbon dioxide. Facultative Ponds are shallow-depth open water systems with Aerobic and Anaerobic zones. This works because algae in this type of pond photosynthesise and gives off oxygen that allows aerobic bacteria to thrive and decompose the organic material further. The bottom layers are anaerobic, allowing digestion to take place as well (Kayombo et al., 2004). Lastly, Maturation Ponds are shallow ponds that use sunlight, high pH, and oxygenation to deactivate pathogens, including faecal coliform bacteria. Treated effluent from the maturation ponds can be used in irrigation or safely discharged into the environment. The Maturation Pond employs sunlight, temperature, and hydraulic retention time for effective pathogen removal (Mondiale La Sante et al., 1987).

2.3.3 Advanced Decentralised Technologies

Advanced wastewater treatment technologies employ mechanical or chemical processes, often combined with biological stages, to effectively treat wastewater and achieve high-quality discharge standards (Tilley et al., 2014). They are able to serve densly populatied urban communities where land availabilty is limited however they require skilled operation, regular maintenance, and higher investment costs is required (Massoud et al., 2009). While not always feasible in low-resource settings, they can be appropriate when technical and financial circumstances allow.

2.3.3.1 Anaerobic Baffled Reactor

An Anaerobic Baffled Reactor (ABR), also known as a fixed bed or fixed film reactor, is an improved version of the conventional Septic Tank with several baffles (Tilley et al., 2014). The baffles force wastewater to flow through several compartments, enhancing the contact time with the sludge and improving treatment efficicieny. The upflow chambers in the ABR boost organic matter removal and digestion, reducing the BOD by up to 90%, far more significant than its removal in a Septic Tank of around 30 to 40% (Tilley et al., 2014).

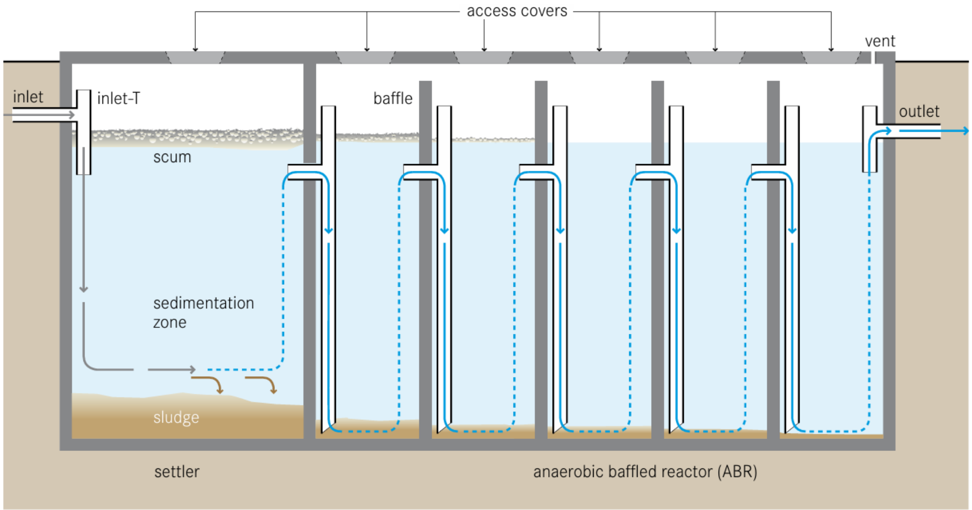


Figure 12: Schematic of an anaerobic baffled reactor (Source: Tilley et al., 2014)

2.3.3.2 Membrane Bioreactor

Membrane bioreactor (MBR) is an advanced wastewater treatment technology that integrates biological treatment with membrane solid and liquid separation (Asif et al., 2022). The technologies use semi-permeable membranes, typically microfiltration (MF) or ultrafiltration (UF), which allow the physical retention of suspended solids, bacteria and, in some cases, viruses, resulting in a high-quality effluent without secondary clarification (Asif et al., 2022). Based on space, energy, and operation considerations, these membranes can be designed as submerged modules directly installed internally in the bioreactor or sidestream modules installed externally (Le-Clech et al., 2006).

The high mixed liquor suspended solids (MLSS) concentrations, the concentration of suspended solids, of 8,000-12,000 mg/L operation capability ensures that the MBR produces higher organic loading rates and reduced reactor volumes, making them much more compact than the activated sludge systems (Meng et al., 2009). The aeration system in MBRs provides oxygen to the microorganisms and shear to prevent membrane fouling, which is one of the primary concerns in MBR operations. Fouling happens through mechanisms such as pore blockage, cake layer growth and biofouling, making periodical backwashing and chemical cleaning essential to ensure the membranes' permeability (Le-Clech et al., 2006; Meng et al., 2009). Although MBR systems require energy and regular maintenance, they are a reliable and flexible option for advanced wastewater treatment, especially in decentralised treatments (Visvanathan et al., 2000).

2.3.3.3 Moving Bed Biofilm Reactor

The Moving Bed Biofilm Reactor (MBBR) is a biological wastewater treatment technology that utilises freely moving plastic conveyors within a reactor to support biofilm growth (di Biase et al., 2019; McQuarrie & Boltz, 2011). These conveyors, typically made from high-density polyethene, are engineered to offer a large protected surface area ranging from 500 to over 1200 m^2/m^3 depending on the type for microbial attachment and activity. The biofilm on the conveyors allows for eliminating organic impurities and nitrogen forms through carbon oxidation, nitrification, and denitrification reactions. Aerobic MBBR systems employ diffused aeration to transfer oxygen and suspend the conveyors, whereas anoxic systems utilise mechanical mixing. Retention screens allow no carriers to escape the reactor, and excess biofilm naturally sloughs off, which regulates the optimum thickness. MBBRs can be designed for varied treatment goals such as single-step carbon removal, nitrification after activated sludge, and pre- and post-denitrification with very high operation flexibility. Their capacity to upgrade existing treatment plants with no significant structural modifications and their stable operation at variable loads shows that they are suitable for centralised and decentralised wastewater treatment systems (di Biase et al., 2019; McQuarrie & Boltz, 2011).

2.3.3.4 Sequencing Batch Reactor

According to Rasheed & Ciroma (2020), the sequencing batch reactor (SBR) is a “variant of the activated sludge system characterised by intermittent flow operation, which, due to its relatively low cost and small footprints, makes it an alternative to the conventional activated sludge process”. It is a process that fills and draws, combining all conventional activated sludge treatment methods, including biological reactions and solid-liquid separation, within a single vessel. In this vessel, treatment processes occur in time sequence rather than separated units, as in the case of conventional continuous flow activated sludge systems. The SBR process is inherently a cyclic operation subjected to the following phases: fill, react, settle, sludge withdrawal and decant, with each phase lasting for designated periods. A noteworthy advantage of this process is that the treatment phases can be rearranged or removed, and the duration of each phase and the number of cycles can be altered depending on the influent dynamics, treatment requirements and overall design goals. Therefore, it provides flexibility, efficiency, reliability, and the ability to produce high-quality effluent (Rasheed & Ciroma, 2020).

The influent wastewater flows into the sequencing batch reactor during the filling phase. This influent, rich in organic matter and nutrients, promotes essential biochemical reactions via mixing and aeration unless the static filling is utilised. If influent wastewater enters the tank without mixing or aeration, this is known as static filling. This method is usually adopted during low-flow periods for energy savings or treatment systems not needing nitrification or denitrification. When discussing instantaneous fill insertion, it may involve a simple dump fill during the fill phase that only serves to establish a high substrate gradient to reduce the risk of filamentous bulking, or, if continuous fill is used through the entire process, to prevent the adverse effects of substrate inhibition, which should primarily be based on the actual wastewater properties and design targets (Rasheed & Ciroma, 2020).

After filling the influent, the aeration phase starts mechanical mixing and introduces aeration. During this time, the SBR acts as a batch reactor until the desired degree of biochemical conversion is reached. During the SBR cycle, most carbonaceous pollutant and nutrient removals happen during the reaction phase, which is the most prolonged phase. In some instances, sludge is withdrawn at the end of the reaction phase, where an appropriate quantity of sludge is removed from the homogeneously mixed reactor. This is the settling phase, in which mechanical mixing and aeration stop, enabling the sludge to settle by gravity into quiescent conditions at the bottom of the reactor. No inflow or outflow occurs during this stage, creating a separate interface between the settled sludge that conglomerates into a flocculent mass and the supernatant transparent layer above (Rasheed & Ciroma, 2020).

2.3.3.1 Up-flow Anaerobic Sludge Blanket

The up-flow anaerobic sludge blanket (UASB) reactor presents a viable alternative for the on-site treatment of domestic wastewater aimed to address the existing restrictive conditions of traditional septic tanks. It has become highly popular on an industrial scale due to the technology's several advantages, such as low sludge accumulation, energy recovery potential, low HRT, and high solids retention time (Nnaji, 2014).

The UASB process operates without the need for packing materials or support structures; it effectively removes high levels of SS and COD by utilising a layer of granular sludge that is both highly active and easily settled (Nnaji, 2014). Unlike many conventional treatment systems, the UASB reactor facilitates vertical flow instead of the typical horizontal flow, enhancing interaction between the anaerobic sludge accumulating and the incoming wastewater. This configuration improves the removal of suspended solids as solid and dissolved organic particles that can be anaerobically biodegraded and trapped within the sludge blanket (Nnaji, 2014).

The reactor design includes a cylindrical or rectangular column and a gas-liquid-solid (GLS) separator. Initially, it is inoculated with a mixture comprising digested, anaerobic, granular, flocculent, or activated sludge. The sludge is introduced at the bottom of the reactor; under suitable conditions, lighter and dispersed particles are washed out while heavier elements are retained. This process limits the proliferation of finely dispersed sludge. It encourages the formation of granules or flocs comprised of inert organic and inorganic matter and small aggregates of bacteria in the seed sludge (Chong et al., 2012).

A dense bed of sludge develops over a span typically ranging from 2 to 8 months, contingent upon operational parameters and the specific characteristics of both wastewater and seed sludge. This bed may have granular or flocculent qualities with enhanced settling capabilities. Above this dense layer lies a zone characterized by diffused growth where particle settling velocities are lower (Chong et al., 2012).

Biological reactions transpire throughout both the active sludge bed and blanket zone. As wastewater flows upward through these areas, soluble organic compounds in the influent are transformed into biogas, predominantly consisting of methane and carbon dioxide. The generated biogas and buoyant sludge supported by trapped gas bubbles are subsequently separated from the effluent via an immersed GLS separator. This separator employs baffles to minimise the wash-out of viable bacterial matter or floating granular sludge while redirecting settled solids back into the reaction zone (Chong et al., 2012).

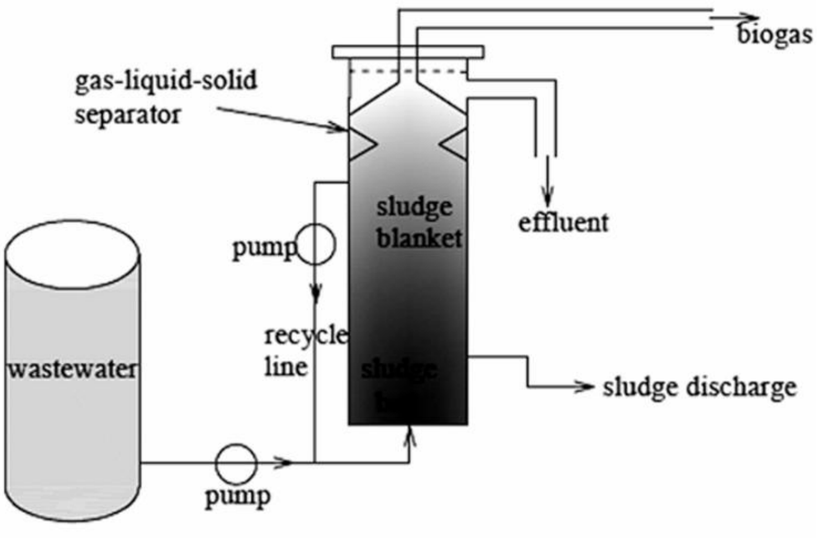


Figure 13: Schematic of a Upflow Anaerobic Sludge Blanket Reactor
(Source: Nnaji, 2014)

2.4. Case Studies from Other Countries

2.4.1 India

A study done by (Shivendra & Ramaraju, 2015) investigated the implementation and sustainability of Decentralised Wastewater Treatment Systems (DEWATS) in two peri-urban community complexes near Bangalore, India. This study assessed DEWATS' effectiveness, cost, and social acceptability within low-income communities. It provides a valuable understanding of the actual operating characteristics of DEWATS in densely populated and underdeveloped areas.

Two sites were selected for the study; the first site (Site 1) was a government housing project with about 600 residents working in cottage industries, and the second site (Site 2) was a residential facility with a population of 40-70 mentally disabled adults. Both sites employed a DEWATS system consisting of a biogas settler, an ABR and planted gravel filters (PGF). The second site incorporated a polishing pond for further tertiary treatment. The systems treated blackwater and greywater from toilets, bathrooms, and washing machines, of which the resulting treated water was gardening and for horticulture requirements and the biogas for domestic energy usage.

Performance monitoring of the DEWATS was done over a period of 3 months to analyse influent and effluent for physico-chemical and microbiological parameters. The results showed that treatment was highly efficient at both sites. At Site 1, BOD decreased from 333 mg/L to 18 mg/L (95% removal), COD was reduced from 601 mg/L to 41 mg/L (93% removal) and SS from 2680 mg/L to 360 mg/L (87% removal). At Site 2, the BOD decreased from 145 mg/L to 25 mg/L (83% removal), COD was reduced from 315 mg/L to 55 mg/L (83% removal), and SS 6960 mg/L to 430 mg/L (94% removal). The higher SS removal observed at Site 2 was likely due to the polishing pond, which enhanced the settling of particles and pathogen removal.

Both site systems also showed significant reductions in microbial contamination, specifically in Escherichia coli (E. coli) and colony-forming units (CFU). CFU counts in influent samples of 800-825/100 mL decreased to 140/100 mL in Site 1 and 100/100 mL in Site 2 meeting discharge requirements. The further removal of E. coli at the secondary and tertiary treatment stages at both facilities demonstrates the effectiveness of these systems in pathogen removal.

The study also highlighted the systems social sustainability. Local citizens were trained to operate and maintain the treatment units, which created a sense of ownership and responsibility. The systems were reported to be affordable and easy to maintain, and they were widely accepted by the residents, who previously had no access to improved sanitation infrastructure. The community was also enhanced through the systems by using the by-products, such as integrating biogas for heating, cooking, etc.

Overall, the study concludes that DEWATS is a technically feasible, economically viable and socially acceptable approach to on-site wastewater treatment in peri-urban areas. Its component-based design, low energy requirement, and resource recover ability make it a sustainable solution to fulfil the sanitation requirements of marginalised communities. The experience in Bangalore proves that DEWATS are able to treat domestic wastewater whilst supporting the environment and the community.

2.4.2 Thailand

Suriyachan et al. (2012) conducted a case study to investigate the potential of decentralised wastewater management (DWWM) systems for urban development in Bangkok, Thailand. Three communities, Pibun Wattana, Tung Song Hong 1, and Bang Na, which represented inner, middle, and outer urban zones, were the focus points of the research. Although relatively small in terms of the number of households involved, these communities, managed by the National Housing Authority (NHA), provide important insights into DWWM performance under different spatial, demographic, and infrastructural conditions.

The study's methodology combined field surveys with expert interviews, document analysis, and structured questionnaires distributed to 378 households. Each site was evaluated based on sustainability indicators such as treatment efficiency, capital and operational costs, reclaimed water use, staff requirements, social acceptance, and service coverage. The systems employed simple treatment methodologies such as activated sludge, stabilisation ponds, and oxidation ditches with relatively small capacities and compact footprints suitable for decentralised applications.

The inner city community of Pibun Wattana operated a small DWWM plant with a 400 m^3/day capacity serving 2,100 residents. However, the plant's actual capacity is 350 m^3/day, and its treatment efficiency is moderate, with the BOD values ranging from 6.0 to 16.8 mg/L and TSS between 4.6 and 14.5 mg/L. The capital costs of the site were USD 23.8 per capita, but with somewhat higher operational costs of USD 0.36/m^3; this is primarily due to intensive labour, which contributes to local employment and the reclaimed water usage only at about 30%.

The Tung Song Hong 1 community in the middle urban zone had a more comprehensive system, with a design capacity of 3,000 m^3/day; however, the operating rate was roughly 43% (1,300 m^3/day). The system serves 15,000 people and utilises aerated lagoons and stabilisation ponds.

Despite having the lowest effluent quality of all three systems with a BOD value of 4.5 to 30.0 mg/L and TSS 12.7 to 25.3 mg/L. The Tung Sung Hong 1 community system achieved the highest reclaimed water reuse rate of 210.6%. Compared to the inner city community of Pibun Wattana, the capital cost was higher at USD 166 per capita, but the operation costs were lower at USD 0.13/m³.

The Bang Na community, located in the outer urban area of Bangkok, operated a medium-sized facility employing an oxidation ditch system with a design capacity of 1,300 m³/day and an actual capability of 1,050 m³/day. The plant served 8,300 persons and showed consistent treatment performance, with BOD and TSS values within sufficient limits. The 67.9% reuse of reclaimed water and moderate operational costs of USD 0.19/m³ also gave this system a balanced environmental and economic performance.

In summary, the (Suriyachan et al., 2012) case study indicates that DWWM systems in Bangkok are highly cost-effective, with construction costs of USD 24-166 per capita being substantially lower than centralised systems costs of USD 200 per capita. The reason for this is mainly due to reduced sewer infrastructure and the use of simpler technologies. The operational costs varied but were manageable depending on system size and staffing models. Additionally, the community's willingness to pay for the DWWM services of USD 0.10–0.12/m³ demonstrated high social acceptance and satisfaction with the provided services. Moreover, the DWWM provided local jobs and preserved open space for recreational or green uses, enhancing the livability of the urban environment.

Although the DWWM has the potential to provide sustainable solutions at several levels in environmental, economic, and social aspects, the study also highlighted that the acceptance of public and institutional remains limited, especially amongst urban planners and government officials who prefer centralised systems. The interviewed experts emphasised the need for DWWM to be incorporated into formal urban planning with better awareness and supportive regulations. On the other hand, regarding sustainability, the DWWM systems performed well in the environmental, economic, and social aspects and demonstrated adaptability across multiple urban densities and settlement patterns.

In conclusion, the study done by Suriyachan et al. (2012) verifies that decentralised wastewater treatment systems can be a viable and sustainable approach to managing urban sanitation, especially when implemented with appropriate design, operation, and community involvement.

2.4.3 Vietnam

A study by Viet Anh et al. (2005) offers an overview of DWWM in Vietnam, covering key institutional frameworks, technological innovations and pilot-scale field implementations. As rapid urbanisation outpaces the capacity of centralised sewerage systems, the paper notes that decentralised approaches have come into the spotlight as viable solutions and, in many cases, a necessary alternative, particularly in peri-urban and underserved regions of Vietnam.

Decentralisation models are of great relevance in the urban context, such as in Hanoi, where the mandatory Sewerage and Drainage Company (SADCO) can only serve about 60% of the population. In this regard, decentralisation comprises a layered responsibility structure, whilst SADCO manages the primary and secondary sewers; the tertiary sewers, onsite systems, and operational support would be the local People's Committees (PCs) and resident's responsibility. The study notes that community participation is a key component in DWWM, where citizens contribute labour or funds to public works, including sewer cleaning, drainage maintenance, and latrine upgrading. Such participatory arrangements are instrumental in mobilising resources and sustaining maintenance.

Of all conventional septic tank alternatives with the most promising technical features, the systems of choice in Vietnam were the Baffled Septic Tank (BAST) and the BAST with Anaerobic Filter (BASTAF). By increasing contact between the wastewater and sludge through internal baffles, these systems improved anaerobic digestion and solids retention and, as a result, treatment performance. Laboratory-scale experiments at the Hanoi University of Civil Engineering indicated that the BAST removing efficiencies of 70–80% for BOD, COD, and SS by BAST is remarkably better than conventional septic tanks under the same conditions. As such, in one lab regime, BAST had an average COD removal rate of 76.1%, compared to a standard septic tank at 48-hour HRT with a removal rate of 59.8% under the same experimental conditions.

Pilot installations confirmed these findings under real-life conditions. The average removal efficiencies of the BASTAF system after 2.5 years of operation in a private household in Hanoi were 70.5% for COD, 71% for BOD, and 83.2% for SS. These findings demonstrated stable treatment performance across varying influent concentrations and minimal desludging with ambient temperatures variable. Although incorporating anaerobic filter chambers in these systems had no significant effect on biological treatment, they effectively retained solids and reduced effluent particle loads. It was particularly advantageous when post-treatment was planned, such as infiltration trenches and planted filters.

Furthermore, the system was deployed in various settings, such as primary schools, high-rise apartments, offices, and rural communities. In one rural village, a BASTAF system treated wastewater from 90 households, including livestock wastewater, discharged into a baffled waste stabilisation pond built out of a fish pond. The quality achieved by the treatment chain was adequate for agricultural reuse, and by utilising native species, it demonstrates the system's adaptability to rural livelihoods.

Design parameters were also included. Regarding the efficiency of the treatment processes, capital costs, and maintenance terms required, a 2-day HRT was found most suitable for treating BAST and conventional septic tanks. Having more than three baffles did not provide much additional performance benefit, resulting in additional costs and increased maintenance complexity. Additionally, the system's adaptability to shutdowns, temperature fluctuations, and hydraulic loading was noted, making it a viable option for households.

In conclusion, the (Viet Anh et al., 2005) study highlights that even though septic tanks are mandatory in all urban housing construction, enforcement and maintenance are weak. Many conventional tanks turned out to be poorly built and undersized, and desludging was neglected, resulting in extremely low treatment performance. Some surveys also reported effluent BOD concentrations of more than 470 mg/L, way above discharge standards. This poor performance is worsened by poor sludge management infrastructure, public unawareness, and lack of design guidance. Conversely, the BAST and BASTAF systems are a more practical means to realise the ground concrete solution for sanitation in urban and peri-urban areas, as long as it is designed and implemented with community participation.

2.4.4 Nepal

(Bright-Davies et al., 2015) studied three DEWATS systems implemented in Nepal in the Sunga, Srikhandapur, and Nala communities. The selected sites were chosen to reflect diversity in planning, implementation, and operational experience in small, urban, and peri-urban settings. The paper critically evaluates the influence of the planning process, community engagement, financing, and institutional support on Nepal's long-term sustainability of decentralised systems.

The Sunga DEWATS, constructed between 2005 and 2006, was Nepal's first-ever community-based wastewater treatment plant and served 200 households in a low-income settlement in the Madhyapur Thimi Municipality. The system consisted of an anaerobic baffled reactor (ABR), a settler, and two vertical and horizontal flow-constructed wetlands to control pollution flowing into the Siddhikali River. However, the relatively simple and effective technical system encountered challenges due to a lack of maintenance, such as reed bed clogging and drying.

Planning was predominantly a top-down affair, and the community engagement in design and ownership afterwards was minimal.

The second site, Srikhandapur in the Dhulikhel Municipality, was built in 2008 and served 200 households. The system incorporated two bio-digesters, horizontal flow reed-bed treatment systems, and a biogas component. This bio-gas was meant to contribute to community management, generating value from wastewater. However, like Sunga, community involvement was low, and the biogas system soon failed after installation. Although a caretaker was appointed, problems continued with drainage blockages, and no effective enforcement of user fees meant challenges in keeping the operations running.

The third site in Nala, finished in 2012, represented a shift towards a participatory planning model following the Community-Led Urban Environmental Sanitation (CLUES) framework. This system served 294 households and comprised an ABR and horizontal gravel-bed constructed wetlands. In contrast with the other two projects, Nala employed a simplified sewerage system to transport blackwater and greywater separately and emphasised strong community engagement throughout the planning, construction and management stages. The community funded 33% of the cost for planning and implementation and participated in selecting the treatment technology. As a result, there was more ownership, better operational strategies and more prominent institutional capacity. A revolving fund provided the Nala Water Supply and Sanitation Users' Committee (WSUC) with the financial resources necessary to oversee the system's functioning.

Across all three systems, the technological configurations exhibited how DEWATS components such as ABRs, constructed wetlands, and biogas digesters could be adaptable. Even though the systems required low energy and capital inputs, long-term effectiveness was greatly affected by the extent of community participation and the quality of operation and maintenance (O&M) planning. Sunga and Srikhandapur, which external agencies initiated, were implemented with little input from the community and lacked upkeep and financial support. On the other hand, Nala's inclusive planning and institutional setup contributed to a more resilient and sustainable system.

In addition, the study highlights widespread barriers to replication and scaling, including limited local government capacity, institutional biases toward centralised or high-tech solutions, and a lack of clear national policies promoting decentralised sanitation. Although DEWATS have been technically successful, the system's adoption in Nepal is low due to a lack of supportive regulatory frameworks and limited vision among donors and government agencies.

Overall, the Nepal case study demonstrates the technical and economic feasibility of DEWATS in dense, resource-constrained urban settings. However, their long-term success depends on careful planning, local governance, sustainable financing of operation and maintenance, and policy support. Comparing these three systems demonstrates that community involvement, especially at the early stages of the planning process, contributes to achieving sustainable decentralised wastewater management.

2.5. Wastewater Treatment in Laos

2.5.1 Overview of Wastewater Generation in Laos

The Laos People's Democratic Republic, or Lao PDR, is a landlocked country in northeast-central region of mainland Southeast Asia. China, Vietnam, Cambodia, Thailand, and Myanmar border the country (Lafont et al., 2025). Based on data from Worldometer.com, in 2025, the population of Laos is an estimation 7,873,046 with a population density of 34 per km^2. The United Nations categorises Lao PDR as a Least Developed Country (LDC), of which countries in the LDC category are labled as low-income nations that experiencing significant structural constraints to sustainable development. This means that as a LDC, Lao PDR receives special access to various forms of international support, including trade assistance, general support and development aid.

Figure 14: Map of Lao PDR (Source: World Bank, 2014)

The capital, Vientiane's rapid and often unplanned expansion, has led to high population density in the downtown and commercial areas. Since the 1990s, the sanitation and drainage networks have improved significantly, thanks to the support from various donors in enhancing basic infrastructure. However, the water quality in urban city drainage and wetlands has deteriorated. The primary sources of pollutants were untreated wastewater discharge from human activities, residential and commercial areas, and small industries. As a result, many open canals in urban areas today now exhibit a noticeably darker colour due to deteriorating water quality (Deevanhxay, 2022).

Approximately 85,000 m^3 of the cities wastewater is unleased daily to the public canals and rivers, half of which is treated (Chanthavilay et al., 2017). The increased pollution levels threaten these waterways' ecosystems, contributing to foul odours, spoiled local landscapes, and increasing health risks for residents who rely on the nearest water body in their everyday lives. Furthermore, the local communities are more likely to contract waterborne infections, especially during the dry season. The quality of the water bodies is anticipated to worsen further due to the increasing flow of untreated wastewater from urbanisation, agriculture practices, and industrial activities (Deevanhxay, 2022).

Despite the rapid evolution of environmental legislation in the Lao PDR, the existing legal framework remains largely general, with minimal specific references to wastewater sanitation concerns. These inconsistencies include contradictory provisions, indistinct or overlapping institutional roles, lack of regulations for implementation, and poor monitoring and enforcement means to guarantee compliance with the legal framework (Baetings & Declan, 2010).

As such, sanitation and wastewater are often neglected in Laos due to the absence of a designated government agency and a lack of leadership regarding high-priority matters such as policy, legislation, responsibilities, and budget allocations. As a result, policy and legal advancements for wastewater sanitation have lagged. The government's ability to execute programs and meet wastewater sanitation coverage objectives predominantly relies on projects or program financing from development partners, as the government's finances for such projects are severely insufficient (Baetings & Declan, 2010).

2.5.2 Existing Wastewater Treatment Infrastructure

Laos employs several types of wastewater treatment systems. In urban areas, the primary method for managing wastewater is on-site treatment systems such as pour-flush latrines and septic tanks, especially for blackwater. Most households in Laos utilise a pour-flush toilet that is either linked to a septic tank or a soak pit, which when full gets emptied or replaced.

Consequently, the water in the drainage system is often tainted with faecal matter and pathogens from latrines and septic tank discharge (ADB, 2021).

Unfortunately, these systems often operate without adequate treatment or maintenance, given that no dedicated separate wastewater collection system exists. Regular desludging of septic tanks is uncommon, given that there are no regulations governing sludge disposal. The residents often take action themselves in discharging the untreated sludge, which goes unsupervised. Therefore, most of the time sludge is disposed directly into open drainage systems or the surrounding environment, including roadsides, rice fields, and wetlands (Chanthavilay et al., 2017).

2.5.2 Existing Decentralised Wastewater Treatment Systems

Between 2009 and 2021, around 29 decentralised treatment facilities were installed in Laos across nine provinces, with 1–200 m³/day treatment capacities, adding to a total national treatment capacity of over 743 m³/day. The technologies were developed by the Lao Institute for Renewable Energy (LIRE), the Bremen Overseas Research and Development Association (BORDA), Japan’s Johkasou systems, and multiple Chinese models, particularly in the Luang Namtha Province. However, little information is publicly available about the system, their operational performance and results (Deevanhxay, 2022).

2.5.3 Legal and Regulatory Framework for Wastewater Management in Laos

The legal and regulatory framework for wastewater management in Lao PDR is fragmented, has limited enforcement, and lacks a national sanitation policy. Multiple institutions with overlapping mandates exist, ranging from the Ministry of Public Works and Transport (MPWT), which oversees urban water supply and infrastructure, to the Ministry of Health (MOH), through Naam Sat, the National Centre for Environmental Health and Water Supply, which is responsible for rural sanitation and hygiene; and the Ministry of Natural Resources and the Environment (MONRE), which governs environmental protection and pollution control. However, none of the agencies regulate or manage wastewater, especially in urban areas. Existing laws, such as the Water and Water Resources Law, revised in 2017, and the Environmental Protection Law, include general provisions for protecting water quality related to and preventing water pollution but do not present specific regulatory frameworks or enforcement mechanisms for wastewater treatment and disposal. While national environmental quality standards and pollution control regulations exist, they are rarely enforced due to a lack of institutional and technical capacity at both central and local levels (Baetings & Declan, 2010; UNESCAP, 2015)

2.5.4 Institutional Framework and Key Stakeholders

An overlapping mandate and poor coordination among key actors characterise the Institutional Framework and Key Stakeholders in Laos. At a national level, MPWT is the lead agency for urban infrastructure, including sanitation planning and service provision, through its Department of Housing and Urban Planning (DHUP). At the same time, the MOH through Nam Saat, is responsible for sanitation and hygiene promotion in rural areas. The regulatory role of MONRE encompasses developing environmental quality and water resources management standards and monitoring pollution control, including wastewater discharge regulations. However, these agencies tend to operate independently, as no single institution has a comprehensive mandate to regulate urban and peri-urban wastewater management nationwide (Deevanhxay, 2022; Baetings & Declan, 2010; ESCAP, UN-Habitat, & Asian Institute of Technology, 2015)

Urban Development and Administration Authorities (UDAAs) within the local government system, such as in Vientiane, are responsible for sanitation service delivery. However, they have limited technical and financial capacity and are ineffective at implementation. Also, the lack of a national technical working group (TWG) dedicated to sanitation tasks has severely impeded coordinated policy development and multi-sectoral planning. Additionally, although decentralisation is nominally part of the government strategy, local authorities are often under-resourced and dependent on project-based support from donors and NGOs. International and non-governmental stakeholders, including BORDA, ADB, JICA, and the World Bank, have been strongly represented in piloting DEWATS and faecal sludge management solutions. However, these initiatives are mostly externally driven and not yet part of national systems (Deevanhxay, 2022)

The role of the private sector in sanitation service delivery, especially in desludging and wastewater treatment, is still largely unregulated. Although many private contractors are working in cities such as Vientiane, there is no effective licensing or quality control mechanism, and illegal sludge disposal into waterways is common because there is no monitoring and little enforcement. At the same time, the institutional environment does not have consistent planning instruments and monitoring mechanisms. As such, the draft Urban Wastewater Strategy and Investment Plan (2015–2030) highlights the need for institutional reform, capacity strengthening, and decentralised technologies; little progress has been made on these initiatives (ESCAP, UN-Habitat, & Asian Institute of Technology, 2015).

2.5.5 Economic and Financial Aspects Regarding Wastewater Treatment in Laos

In Lao PDR, wastewater treatment is predominantly publicly funded, with low-cost recovery and reliance on donor funding (ADB, 2021; Baetings & Declan, 2010). Public investment in urban sanitation is low and relies on funding from external development partners rather than facilitating nationwide or city-based financing plans for wastewater infrastructure. Urban sanitation projects have mainly been implemented through donor-supported pilot initiatives lacking integration with national planning; wastewater treatment facilities are urgent examples of evidence at the present moment. Where user fees are applied, they are commonly flat-rate and do not even cover essential operation and maintenance (O&M) costs. Metering and volumetric billing are non-existent, constraining revenue generation and limiting the potential to sustainably scale services. In additon, The World Bank (2015) states that no licensing, monitoring, or quality standards for private providers also worsens viability and ecological alignment (Baetings & Declan, 2010; Deevanhxay, 2022)

3 Methodology

3.1 Methodology

This study uses qualitative, descriptive, and comparative research design to explore a range of decentralised wastewater treatment system options for urban, peri-urban, and rural areas of Laos, focusing on Vientiane, the Capital city. Since no primary data was collected, the research is based on a literature-based methodology. Interviews or site visits were neither conducted nor performed, so the user perspective could not be captured, local operational issues could not be documented, and real-time data could not be gathered. Thus, the study relies on secondary sources to investigate decentralised wastewater treatment technologies and evaluate their feasibility for application in Vientiane, Laos.

The research aims to connect technical theory and local applications by identifying systems used worldwide, particularly in regions with similar socioeconomic and environmental conditions, and assessing their contextual suitability for Vientiane, Laos.

Secondary data was gathered from various academic, institutional, and technical sources, including academic journal articles, development agency reports, grey literature, technical manuals and project documentation (see Table 5). Academic journals provided the underlying theory and system-level performance metrics. At the same time, organisations such as the ADB, WHO, and BORDA provided case-specific implementation data, policy insights and institutional frameworks.

The literature was selected based on its relevance to decentralised wastewater treatment, similarity of context, technical credibility, and recency of publication, with a focus on works published between 2005 and 2024. Case studies on India, Thailand, Vietnam and Nepal were also selected due to similarities between these countries and Laos regarding the development stage, infrastructure challenges, and decentralisation potential.

Source Type	Examples	Purpose
Academic Journals	Chan et al. (2008), Metcalf & Eddy (2014), Smol et al. (2020), etc.	Theoretical foundation, technical parameters
Developement Reports	ADB (2021), WHO (2023), etc.	Contextual background
Technical Manuals	BORDA, etc.	System design
Case Studies	India, Thailand, Vietnam, Nepal	Real world implementation and feasibility
Local Reports	Deevanhxay (2022), Chanthavilay et al. (2017), etc.	Urban sanitation conditions in Vientiane

Table 5: Examples of types of sources used in the study (Source: own work)

A multi-criteria assessment framework is utilised to evaluate the feasibility of decentralised wastewater treatment systems. This framework included five general dimensions for assessing sanitation technology which are technical feasibility, economic feasibility, environmental performance, social acceptability, and institutional compatibility.

Technical feasibility assessed each system’s pollutant removal efficiency, adaptability to the climate and infrastructure of Vientiane, construction and operation complexity. Economic feasibility covered capital costs, O&M expenses and access to materials and labour. Environmental performance evaluated the potential to reduce pollution, recover resources including water, nutrients, and energy, and overall ecological impact. Social acceptability focuses on ease of use, cultural appropriateness, user engagement capacities, and community management capacity. Institutional compatibility is the alignment with existing policies/regulations, decentralisation frameworks, and governmental or municipal support.

Based on existing literature and case studies data, each technology is evaluated using a qualitative three-tier scoring system: low, moderate, or high feasibility (see Table 6). Scoring thus enabled a structured comparison between the technologies, revealing patterns and priorities shown and discussed in the Results chapter.

Score	Description
*	Low feasibility: not recommended in local context
**	Moderate feasibility: potentially applicable
***	High feasibility: strongly suited for Vientiane

Table 6: Feasibility scoring scale (Source: own work)

A SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis is conducted on three shortlisted technologies along with the scoring framework. These included Anaerobic Baffled Reactors, Constructed Wetlands, and Septic Tanks, which proved to be the most promising options in the preliminary investigation. The SWOT analysis provided a strategic lens to examine both the strengths and weaknesses of each system, such as robustness and maintenance, and the opportunities and threats, such as the need for land and public knowledge, policy support and financing, at a landscape level. A scoring matrix and careful analysis enable a well-rounded evaluation to guide technology selection.

To further localise the findings and generate spatially relevant recommendations, the capital of Vientiane is conceptually divided into three urban typologies: urban core, peri-urban zones and rural-fringe settlements. Each zone is categorised according to density, land use, infrastructure availability, and socio-economic conditions. In Vietnam and Thailand, typology-based site planning approaches have also been developed to enhance the implementation frameworks for decentralised sanitation.

The research approach matched the study's three primary goals to ensure consistency and focus. The first objective, identifying decentralised wastewater treatment systems suitable for Laos, was achieved through an extensive literature review and technical description. The second objective, assessing the feasibility of implementation, was supported by the multi-criteria framework and SWOT analysis for the second objective, assessing the feasibility of implementation. Lastly, the third objective, recommending suitable options for Vientiane, Laos, was based on joint consideration of the scoring results and lessons from international case studies.

Although the study aims to ensure academic rigour and practical relevance, which are used as a guideline for data gathering and analysis to come up with meaningful information, the study also has its limitations. It lacks practical fieldwork, so the evidence relies entirely on secondary data. As such, performance and feasibility metrics are only suggestive and should not be assumed to represent ground conditions in Laos fully. Moreover, the analysis does not include stakeholder perspectives such as those of municipal authorities, local communities, or service providers. These limitations have been noted and discussed in the Discussion chapter, along with recommendations for future research.

4 Results and Discussion

4.1 Results and Discussion

4.1.1 Overview

This chapter presents the results of a literature-based analysis of decentralised wastewater treatment technologies in Vientiane, Laos. The analysis is based on a multi-criteria framework that includes technical, economic, environmental, social, and institutional feasibility. The technologies are evaluated using a qualitative scoring matrix and further supported by SWOT analyses for the systems that ranked highest. The results are then further contextualised using international case studies. The aim is to identify how different technologies can respond to the local conditions and constraints, and by doing so, it enables suggestions for practical recommendations of decentralised wastewater installation options in Vientiane, Laos.

4.1.2 Comparative Feasibility Assessment

The comparative assessment evaluates all nine decentralised technologies, which revealed a substantial variation in their suitability for Vientiane. Table 7 summarises the qualitative scores assigned across the five evaluation criteria mentioned in chapter 3 based on the technical literature, case studies, and experience from implementation in similar infrastructure, environment, and development contexts.

Technology	Technical	Economic	Envrionmental	Social	Institutional	Overall Feasibility
ABR	***	**	***	**	**	High
CWs	**	***	***	***	**	High
Septic Tanks	*	***	*	**	*	Moderate
MBR	***	*	***	*	*	Low
MBBR	***	**	**	**	*	Moderate
SBR	***	*	***	*	**	Low
WSPs	*	**	***	***	**	Moderate-High
Anaerobic Filters	**	**	**	**	*	Moderate
Pit Latrines	*	***	*	**	*	Low

Table 7: Summary of decentralised technology feasibility score (Source: own work based on synthesis of literature reviewed in Chapter 2)

From this assessment, Anaerobic Baffled Reactors (ABRs) and Constructed Wetlands (CWs) are the most suitable technologies for decentralised wastewater treatment in Vientiane. Both scored high across technical, environmental, and institutional criteria and exhibits promising to adapt to the local urban and peri-urban context based on synthesis of literature reviewed. In contrast, advanced systems such as Membrane Bioreactors (MBRs) and Sequencing Batch Reactors (SBRs), despite obtaining high technical and environmental performance ratings, exhibited low economic and institutional feasibility scores, which corresponds to the limited resources and skills available in Laos.

Next are septic tanks, even though they scored lower than other technologies. They are still Lao’s most commonly used on-site sanitation system and are well-rated in cost and familiarity aspects. The septic tank can offer excellent cost-effectiveness and usability, making it a popular option for communities. However, the septic tank offers limited treatment effectiveness unless integrated with secondary treatment units. In addition, because septic tanks are the standard and can easily be improved at a relatively low cost, they are an important transitional technology in the future of decentralised wastewater treatment. On the other hand, technologies like Moving Bed Biofilm Reactors (MBBRs) and Anaerobic Filters are moderately feasible but lack the institutional support and technical capacity needed to implement them on a larger scale.

4.1.3 Case Study Insights

Case studies from India, Thailand, Nepal, and Vietnam are further examined to enhance the relevance of the comparative results.

DEWATS were successfully implemented in low-income, high-density peri-urban areas of India. The Shivendra & Ramaraju (2015) study reported over 90% removal of BOD and COD using ABRs, planted gravel filters, and polishing ponds. The systems were easily managed, socially acceptable, and operated by trained locals. Resource recovery made these approaches even more sustainable. The Indian experience highlights the importance of low-energy, modular systems in densely populated urban areas, especially when combined with community-based management.

Thailand's experience illustrates how decentralised systems perform within planned urban developments. Suriyachan et al. (2012) assessed DWWM in three Bangkok communities differing in urban density. As confirmed by the study, space and cost constraints can be accommodated through systems such as oxidation ditches and aerated lagoons. This allowed for much lower capital costs than conventional centralised approaches, and water reuse in some areas. Despite initial success, institutional resistance and limited policy integration hindered wider adoption. These results emphasise the need to incorporate decentralised solutions into city planning and regulatory frameworks.

In Vietnam, decentralised systems such as baffled septic tanks (BAST) and BAST with anaerobic filters (BASTAF) have shown strong technical performance and durability. Viet Anh et al. (2005) reported that, at field test conditions of a BASTAF system, it attains more than 70% removal efficiency for COD and BOD, with little need for desludging. Community involvement in the maintenance of these systems and integration with agriculture were essential to longer-term sustainability. The Vietnamese case study also illustrates how institutional layering, where national agencies manage trunk infrastructure while local authorities and residents handle decentralised units, can enable sustainable operations.

Lastly, in Nepal, the success of decentralised systems varied depending on governance and community engagement. Bright-Davies et al. (2015) conducted a comparative study which found that systems without community involvement and financial autonomy deteriorated quickly. Specifically, the Nala project was able to sustain functionality because it was developed through the Community-Led Urban Environmental Sanitation (CLUES) framework, establishing local ownership, financing and institutional capacity for operations, maintenance, repairs, and rehabilitation. This shows that social mobilisation and participatory planning are key elements for decentralised systems to be resilient.

The international case studies collectively reinforce three necessary conditions for successful decentralised sanitation: technology selection is well-suited to the local spatial and environmental constraints, community engagement and ownership, and institutional support structures that involve planning, monitoring, and financing mechanisms.

These understandings are especially relevant for Laos as most of the countries face similiar challenges, such as rapid urbanisation, limited sewer coverage, decentralised administrative frameworks, and limited financial and technical resources. The Indian and Vietnamese experiences confirm the context that low-energy, modular systems such as ABRs and baffled tanks are well-suited to such contexts. The Thai example indicates that integrating decentralised systems is possible even in higher-density areas if political and regulatory support exists to design them accordingly. Nepal's experience, particularly the impact of the Nala project, shows the importance of a participatory approach to planning, which must be a key element in Vientiane's approach to sanitation.

The common theme across all the cases is that decentralised technologies alone will not be enough. Long-term success depends on how they are governed, financed, and maintained. For Vientiane, this means enabling supportive policies for decentralised sanitation, institutional coordination between national and municipal authorities, and community ownership of their systems. Decentralised systems, with the right balance of technical planning and participatory governance, can comprise dynamic, sustainable, and socially inclusive components of the city's sanitation future.

4.1.4 SWOT Analysis of Key Technologies

A SWOT analysis is conducted for Vientiane's three most promising, technically feasible options for decentralised wastewater treatment, anaeorobiv baffled reactor, constructed wetlands and septic tanks. This analysis will further elaborate on each system's strengths and weaknesses and describe external opportunities and threats impacting its potential implementation in the local context.

4.1.4.1 Anaerobic Baffled Reactors

Strengths	**Weaknesses**
- High removal efficinecy for BOD and COD - Compact design - Low energy requirements	- Requires regular desludging and proper sludge handling - Limited familiarity with the public - Require skilled personnel for design, construction and care
Opportunities	**Threats**
- Can be integrated in schools, apartments, or institutional facilities - Suitable for pilot programs	- Lack of regulatory enforcement for desludging may lead to failure of system - Lack of sufficient O&M in Vientiane - Institutional fragmentation may delay adoption

Table 8: SWOT analysis of the anaerobic baffled reactor (Source: own work)

ABRs fit well in Vientiane’s dense urban areas, especially for use in institutional and communal situations. Their robustness and treatment efficiency make them suitable for medium-scale applications. However, ensuring long-term success means that training, regulation, and oversight mechanisms must support regular desludging and upkeep.

4.1.4.2 Constructed Wetlands

Strengths	**Weaknesses**
- Low-tech, nature-based system with high public acceptance - Strong performance in pathogen and nutrient removal - Low maintenance requirements	- Requires larger land area than most other technologies - Seasonal variation in performance as it is influenced by hydraulic loading - Due to lack of public awareness, may be mispercieved as swaps or stagnant zones
Opportunities	**Threats**
- Ideal for peri-urban areas - Effluent can be reused for irrigation or landscaping - Potential integration with environmental education and landscape planning	- Urban expansion may reduce land availability in future - Bad management may lead to community rejection or failure - Lack of technical design standards may affect effectiveness

Table 9: SWOT analysis of the constructed wetlands (Source: own work)

Constructed wetlands can suit Vientiane’s peri-urban setting well as land is more available and ecological systems are socially welcomed. Long-term community engagement is supported through their environmental and aesthetic value. However though, proper design and education are important to avoid system misuse or failure.

4.1.4.3 Septic Tanks

Strengths	**Weaknesses**
- Familiar and widely accepted technology in both urban, peri-urban and rural areas - Low capital cost and easy to construct with local materials - Can be installed at household level	- Offers minimal treatment unless paired with secondary systems - Is often poorly maintained and neglected for desludging - Contributes to groundwater contamination
Opportunities	**Threats**
- Can be upgraded with filters, wetlands, or anaerobic modules - Suitable for transitional zones or low-income housing developments - Can form part of broader DEWATS clusters	- Unsupervised sludge disposal threatens public and environmental health - Weak regulatory management may limit quality and maintenance enforcement

Table 10: SWOT analysis of the septic tank (Source: own work)

Although they have limited capacity as a stand-alone treatment system, septic tanks are common and widely accepted in Vientiane by the public. With technical upgrades and improvements in regulations, they are able to be transitional or complementary systems.

4.1.5 Interpretation and Implications

This study demonstrates that DEWATS are technically feasible and contextually appropriate solutions in addressing the sanitation challenges of Vientiane in Laos. Various technology options are available. However, their feasibility depends greatly on technical complexity, cost, land availability, institutional support, and user acceptance. Using a qualitative evaluation framework based on global case studies and contextual analysis, this research identifies which systems can be successful and under what conditions they are most likely to succeed.

Anaerobic Baffled Reactors and Constructed Wetlands were the most promising technologies based on the technologies assessed. ABRs are very efficient in treating and have compact designs with low energy requirements, making them suitable for medium- and high-density environments. In addition, the ability for their structure to be modular allows for implementation stages and scalability, which can be valued in fast-developing urban centres like Vientiane. However, their successful operation depends on reliable desludging services and continual technical oversight. Without institutional mechanisms for operation and maintenance, ABRs are likely to deteriorate, no matter how well-designed they might be.

In contrast, CWs are nature-based solutions that provide social and environmental co-benefits and minimal maintenance. They are particularly suitable where moderate land availability and community involvement are possible. However, they must be designed and managed carefully to avoid problems like clogging and breeding mosquitoes. Moreover, even the most environmentally responsible systems will underperform over time when no clear ownership exists for maintaining them.

While domestically widespread and culturally acceptable in Laos, Septic tanks ranked low in effectiveness in their conventional technologies. Their treatment performance is heavily compromised by poor construction quality, irregular desludging, and unregulated effluent discharge. Still, they have potential as transitional systems and could be improved with anaerobic filters or along with constructed wetlands for secondary treatment. Their simplicity and low cost are still important, but only together with better design standards and regulatory scrutiny.

In contrast, Membrane Bioreactors, Sequencing Batch Reactors and other high-tech systems show excellent pollutant removal performance but are currently poorly matched to Vientiane's institutional and economic environment. Their reliance on advanced components, skilled operators, and continuous energy supply offers significant barriers to implementation. Such systems may find a place in specialised or high-value developments such as hospitals, government buildings, or commercial complexes; they are, however, not currently recommended for widespread adoption.

The analysis further shows that possessing technical feasibility does not always translate to success. Decentralised wastewater systems need strong governance, defined institutional roles and responsibilities, sustainable financing, and community engagement. Without these, even well-designed systems are unlikely to perform consistently or be sustained over time. Having learned from experiences in countries like Nepal and Vietnam, we can confirm that decentralised solutions perform well when combined with participatory planning processes and long-term maintenance frameworks.

5 Conclusions and Recommendations

5.1 Conclusion

To conclude this paper, the study aimed to assess the feasibility and applicability of variations for treating the growing sanitation challenges of Vientiane, Laos. By using qualitative, literature-based methodology, the study examined nine decentralised technologies and analysed them across five fundamental dimensions which are the technical, economic, environmental, social, and institutional feasibility. In addition, international case studies provided grounded insights into real-world implementation and the sustainability of results.

The findings suggest that decentralised wastewater systems can provide practical and contextually relevant alternatives to traditional centralised systems, especially in urban and peri-urban contexts where infrastructure expansion is limited by cost, capacity and urban settings. Anaerobic Baffled Reactors and Constructed Wetlands show the most promising feasibility based on the technologies reviewed. These technologies require little energy, are flexible and can provide reliable treatment performance with the proper institutional and community support.

Septic tanks are a standard in Vientiane but are typically poorly designed for adequate treatment. However, additional treatment systems, such as anaerobic filters or stabilisation ponds as secondary treatment components, can be helpful to intermediate technologies, particularly in peri-urban and rural settings.

In contrast, more advanced technologies like Membrane Bioreactors and Sequencing Batch Reactors, whilst theoretically advantageous, are not yet broadly applicable for Laos due to prohibitively high capital and operational costs, high energy inputs, and the need and reliance on skilled operation and maintenance personnel.

In summary, this paper draws attention to the fact that success is not based on the technology selection and its feasibility alone. Lessons from international case studies demonstrate that a wastewater system with long-term sustainability relies on community participation, institutional clarity, maintenance planning, and supportive policy frameworks. In other words, decentralised sanitation solutions should be viewed as both technical interventions and integral components of social and institutional systems.

5.2 Recommendations

Based on the findings and analysis from the study, the following recommenadation are offered to improve effective decentralsied santion on Vientiane, Laos:

1. Establish clear institutional roles and responsibilities.
2. Introduce performance monitoring and regulation.
3. Involve communities in planning and operation.
4. Invest in and build skills and technical capacity.
5. Strengthen community engagment and ownership.
6. Include decentralised systems into urban planning.

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Annex

No	Location	Type of Technology	Commercial Name	Treatment Capacity (m^3/day)	Number of users	Start of Operation	Province
1	Dormitory Residence, Faculty of Engineering, NUOL	Anaerobic treatment	CBS	10	125	2009	Vientiane Capital
2	Thongkhankahm Village, Unit 11, 12, 13	Anaerobic treatment	CBS	11.2	146	2010	Vientiane Capital
3	Khualoung Primary School (SBS1.0)	Anaerobic treatment	SBS	7	116	2010	Vientiane Capital
4	Student Dormitory, Northern Agriculture and Forestry College	Anaerobic treatment	SME	15	208	2011	Luang Prabang Province
5	Operation Camp of THPC	Anaerobic treatment	SME	70	700	2011	Khammouane Province
6	Expansion Camp of THXP	Anaerobic treatment	SME	30	300	2011	Khammouane Province
7	Khoualoung Temple/School and Village	Anaerobic treatment	CBS	26	455	2012	Vientiane Capital
8	Hin Huep District, Department of Water Resources (DWR), MONRE	Anaerobic treatment	CBS	3	66	2013	Vientiane Province
9	Nam Papa State Enterprise Attapeu (NPSE)	Anaerobic treatment	CBS	14	163	2014	Attapeu Province
10	Nam Papa State Enterprise Attapeu (NPSE)	Anaerobic treatment	CBS	14	235	2014	Attapeu Province
11	National Academy for Politics and Public Administration (NAPPA)	Anaerobic treatment	RESan	2 x 80	1600	2014	Vientiane Capital
12	Xe-Pian Xe Namnoy Hydroelectric Power Plant Project	Anaerobic treatment and Gravel filter	RESan	-	-	-	Attapeu Province
13	Navieng Village	Anaerobic treatment	CBS	14	161	2015	Houaphan Province
14	Health and Science College	Anaerobic treatment	RESan	10	500	2015	Luang Prabang Province

15	Xe-Pian Xe Namnoy Hydroelectric Power Plant Project	Anaerobic treatment	RESan	8	150	2015	Attapeu Province
16	Lao Disabled Women Development	Anaerobic treatment	RESan	6.4	80	2015	Vientiane Capital
17	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ); Lao PDR, Vientiane (Lao-German House)	Anaerobic treatment	RESan	1.5	50	2015	Vientiane Capital
18	World Bank	Anaerobic treatment	RESan	10.2	-	2015	Vientiane Capital
19	Hospital, Xekong, Provincial	Anaerobic treatment	HoSan	35	50	2016	Xekong Province
20	Pakhoatai Primary School	Anaerobic treatment	SBS-Lite	1	220	2016	Bokeo Province
21	Luang Prabang Night Market	Anaerobic treatment	RESan	5	-	2017	Luang Prabang Province
22	Huaydin Village Primary School	Anaerobic treatment	SBS-Lite	-	-	2017	-
23	Kuay Village Primary School	Anaerobic treatment	SBS-Lite	-	-	2018	-
24	Angnoi Village Primary School	Anaerobic treatment	SBS-Lite	-	-	2018	-
25	Luang Namtha District	-	-	-	-	2018	Luang Namtha Province
26	Huaysay District	-	-	-	-	-	Bokeo Province
27	Wattay International Airport, International Terminal	Anaerobic and Aerobic treatment	Johkasou	200	-	-	Vientiane Capital
28	Wattay International Airport, Domestic Terminal	Anaerobic and Aerobic treatment	Johkasou	50	-	-	Vientiane Capital
29	Sethathirath Hospital	Anaerobic and Aerobic treatment	Johkasou	42	-	-	Vientiane Capital

Table 11: Existing decentralised treatment facilities in Laos (Source: Deevanhxay, 2022)

Summary

This paper evaluates the potential for decentralised wastewater treatment systems (DEWATS) as an alternative to the conventional centralised treatment infrastructure for Vientiane, the capital city of Laos. Rapid urbanisation, weak financial and technical capacity, and a lack of centralised sewerage systems have resulted in the indiscrimination and unregulated discharge of untreated wastewater, severely threatening public health and the environment. To that end, the relevance of decentralised technologies in Vientiane's socio-economic, environmental, and institutional landscape is assessed.

The assessment adopts a multi-criteria framework based on the technical, economic, environmental, social, and institutional dimensions. A qualitative scoring matrix was applied to nine decentralised technologies, further supplemented by SWOT analyses for best-performing and suited technologies. Results show that Anaerobic Baffled Reactors (ABRs) and Constructed Wetlands (CWs) have the highest overall feasibility from their known reliable performance, operation, and compatibility with urban and peri-urban environments. Compared to other technologies, Septic Tanks were ranked lower in the evaluation; however, because they are still the most commonly used on-site system in the city and have a high potential for upgrading and improvement for a lower cost, it makes them a transitional system.

These findings were contextualised using international case studies from India, Thailand, Nepal and Vietnam, highlighting how technical performance cannot be disassociated from governance structures, financing mechanisms and community engagement. The study finds that just the selection of the appropriate technological solution is insufficient for the successful implementation of decentralised systems in Vientiane and that the strengthening of institutional coordination, the development of technical capacity, and the establishment of long-term maintenance frameworks plays a crucial role in the long-term sustainability of such systems. These recommendations hope to inform future policy, planning, and investment decisions concerning decentralised sanitation infrastructure for Laos.

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DECLARATION

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