EVALUATE THE ENVIRONMENTAL FOOTPRINT OF TREATED MUNICIPAL SLUDGE

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Civil Engineering (Environmental) with Honours

Faculty of Engineering and Green Technology
Universiti Tunku Abdul Rahman

May 2024

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"EVUALUATE THE ENVIRONMENTAL FOOTPRINT OF TREATED MUNICIPAL SLUDGE"** was prepared by **GOH SIEW YINN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Civil Engineering (Environmental) with Honours at Universiti Tunku Abdul Rahman.

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ACKNOWLEDGEMENTS

I would like to thank everyone who had contributed to the successful completion of this project. I would like to express my gratitude to my research supervisor, Dr. Guo Xinxin and co-supervisor, Dr. Wong Lai Peng for their invaluable advice, guidance and their enormous patience throughout the development of the research.

In addition, I would also like to express my gratitude to my loving parents and friends whose encouragement and unwavering support have been my pillars of strength throughout this journey. I also extend heartfelt thanks to Cik Siti Fairuz binti Zainudin, Encik Md Rosmawi Yaakub and Encik Mohd Anas Farhan bin Ismail for their assistance during data collection and providing feedback. Their contributions have been invaluable.

Lastly, I would like to express my gratitude to UTAR for providing the necessary resources and facilities that facilitated the smooth progress of this project. I am profoundly grateful to each and every individual who has played a role, no matter how big or small, in this journey. Your support has been a beacon of light, guiding me towards the successful culmination of my final year project.

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ABSTRACT

Sludge management presents a significant challenge in the wastewater sector, particularly with the escalating human population leading to increased sludge generation, resulting in waste management issues. In response, many developed countries are shifting towards sustainable practices, utilising technology and exploring alternative methods for treating and disposing of municipal sludge, aiming to phase out landfilling and embrace resource recovery. Life Cycle Assessment (LCA) emerges as a crucial tool in enabling a comprehensive analysis of each process stage to identify the environmental hotspots and drive sustainable development. However, Malaysia lacking comprehensive policies and regulations for resource recovery in the water sector, with limited comparative LCA studies assessing the environmental impacts of various sludge management practices in wastewater treatment plants. This study provides an overview of sludge management in Malaysian wastewater treatment plants and applied LCA to assess its environmental performance. The objectives of the study are to identify the life cycle inventory of sludge management using GaBi software and evaluate the environmental impact indicators of different sludge management using the CML2001 method. LCA of the study was conducted in a gate-to-grave manner, which focused on sludge management from sludge dewatering to its end life. The input and output data for the sludge management process were sourced from a site study conducted at a wastewater treatment plant in Kuala Lumpur, supplemented by the GaBi database and literature sources. Global Warming Potential, Abiotic Depletion (fossil), Acidification Potential, Human Toxicity and Marine Aquatic Ecotoxicity Potential were the five environmental impact indicators analysed in this study. The life cycle inventory analysis (LCIA) revealed that landfilling presented the highest environmental impacts due to methane emissions from landfill degradation and leachate contamination, while incineration offered waste volume reduction and was sustainable for energy recovery but posed air pollution risks. Land application of sewage sludge demonstrated the lowest environmental impacts by substituting fertiliser. However, there was a risk of human toxicity due to the presence of heavy metals. For Global warming potential indicator, landfilling yielded the highest (1084.56 kg CO_2, eq), followed by incineration (220.09 kg CO_2, eq) and land application (182.06 kg CO_2, eq). Acidification potential indicator showed that landfilling exhibiting higher value than land application application (0.221 kg SO_2 eq and 0.916 kg SO_2 eq respectively). Overall, land application emerged as the most sustainable alternative for sludge management for the wastewater sector, offering the potential for adoption to promote environmental sustainability.

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LIST OF SYMBOLS / ABBREVIATIONS

AD	Anaerobic digestion
ADPf	Abiotic Depletion (fossil)
AP	Acidification potential
CO_2	Carbon dioxide
CN	China
DE	Germany
DOE	Department of Environment
DOSM	Department of Statistics Malaysia
DS	Dry solids
EU	Europe
FRIM	Forest Research Institute Malaysia
GHG	Greenhouse gas
GLO	Global
GWP	Global warming potential
HTP	Human toxicity potential
IWK	Indah Water Konsortium
JPSPN	Jabatan Pengurusan Sisa Pepejal Negara
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MAETP	Marine Aquatic Ecotoxicity Potential
MHLG	Ministry of Local Government and Housing
MIDA	Malaysian Investment Development Authority
MY	Malaysia
MoU	Memorandum of understanding
N_2O	Nitrous oxide

NH_4	Methane gas
PAAB	Pengurusan Aset Air Berhad
SPAN	National Water Services Commission
TS	Total solid
VC	Volatile solids
WWTP	Wastewater treatment plant

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Efficient management of solid waste creates a significant economic challenge worldwide, especially with the increasing global population. According to information provided by the Malaysian Investment Development Authority (MIDA) in 2023, on average, every individual produces around 0.74kg of waste per day, with amounts varying from 0.11kg to 4.54kg. Every year, approximately 2.01 billion metric tonnes of municipal solid waste are generated globally, of which 33% need proper environmental management (MIDA, 2023). Insufficient planning and financial support in waste management can result in poorly functioning facilities, which can cause environmental pollution and put public health at risk. The population of Malaysia is expected to rise by 2.1% in 2023, hitting around 33.4 million from 32.7 million in 2022 (Bernama, 2023), showing a rising need for waste management facilities for solid waste and wastewater. Sewage sludge, a residue from sewage treatment facilities, contains heavy metals, organic material, pathogens, nutrients, and high levels of water (Rorat et al., 2019).

In Malaysia, more than 80% of solid waste from cities is thrown away in landfills because they are traditional, inexpensive, and useful in rehabilitating landscapes, especially for sewage sludge. RM1.9 million has been designated by the government for solid waste collection and public cleansing (MIDA, 2023). Nonetheless, JPSPN has noted 137 active landfills, which includes 21 sanitary landfills, with 174 landfills already shut down according to MIDA in 2023. Another effective way to manage waste is through waste-to-energy (WTE) incineration, which can decrease municipal solid waste by 80%-95%. Nevertheless, there has been limited funding allocated to projects involving incineration, resulting in just five operational incineration facilities in Malaysia, such as those located in Pulau Langkawi, Pulau Labuan, Cameron Highlands, Pulau Pangkor, and Pulau Tioman (MIDA, 2023).

Aligned with waste management reduction goals, Indah Water Konsortium (IWK) operates within the water sector, aiming to achieve 100% sludge and 33% treated effluent recycling by 2030 (Indah Water Konsortium, 2022). Collaborating closely with the government and industry experts, IWK explores alternative, environmentally friendly methods for municipal sludge management. Notably, IWK has initiated the reuse of sewage sludge in 13 regional plants to conserve water, energy, and the environment (Sustainability Report 2022, IWK). IWK has maintained ongoing partnerships with academic researchers, such as those from the University Putra of Malaysia, to explore various facets of wastewater management. Collaborations like transforming sludge into organic stabilized fertilizers suitable for land application, enhancing sludge to serve as a soil amendment to improve sandy and degraded soil conditions, co-composting sewage sludge, and assessing the efficacy of utilizing sewage sludge in rubber plantations (Azman et al., n.d.).

In order to improve the environmental impact of sludge management, it is crucial to conduct thorough evaluations of the entire life cycle of the product or system. Lifecycle Assessment (LCA) is a useful instrument that enables the assessment of environmental and financial consequences throughout all phases. In recent times, researchers have extensively used LCA methods to pinpoint environmental factors and evaluate the effects of wastewater treatment activities and sludge handling (Rashid et al., 2023). This research will concentrate on carrying out a life cycle evaluation of municipal sludge management, investigating from the dewatering phase to the sludge's end-of-life phase. By utilizing LCA, industry stakeholders can compare the environmental effects of different sludge disposal methods and pinpoint the most efficient solutions based on the results of the LCA analysis. Adopting environmentally friendly methods in handling sludge is crucial for improving the sustainability of sewage plants and waste generation.

1.2 Importance of the Study

There has been a noticeable increase in worldwide interest in the energy usage of wastewater treatment plants (WWTPs) and the carbon footprint related to sludge management (Smith et al., 2018). Malaysia has incorporated its dedication to decreasing carbon footprints into its policy framework, in line with worldwide sustainability efforts, such as the Five-Year Malaysia Plan. This plan emphasizes the importance of waste reduction strategies as essential elements of larger environmental goals. Recent advancements in Malaysia indicate a growing acknowledgment of the need for sustainable waste management, with efforts emphasizing waste minimization and improved energy utilization. In this situation, it is crucial to prioritize strong data collection and careful resource selection for WWTPs to accurately gauge energy usage and carbon emissions. Despite making progress, there is still a lack of extensive understanding of sludge management practices in Malaysia. At present, the majority of generated sludge is simply thrown away in landfills because it is both cost-effective and easy to manage. On the other hand, less common approaches like burning, turning into compost, spreading on land, and reusing for building materials are mostly being studied and have not been widely used across the country. This highlights the importance of performing a Life Cycle Assessment (LCA) study in the field of sludge management. This method provides a complete structure for assessing the carbon footprint of different activities and for facilitating more sustainable decision-making in alignment with Malaysia's environmental goals.

1.3 Problem Statement

Malaysia's current waste management system is encountering major difficulties because of increasing greenhouse gas (GHG) emissions, with a focus on methane gas produced from organic waste decomposition in landfills, and the growing energy needs of the expanding population. A study done by Yong et al. (2019) shows that in Malaysia, 50% of landfills are open dumping sites, 30% are user-controlled tipping sites, 12% are controlled landfills with daily cover, and 5% each are sanitary landfills with and without leachate treatment facilities. Most of the sewage from cities is currently being thrown away in landfills, which becomes increasingly harmful as the amount of waste being disposed of rapidly grows. Incomplete sewage sludge breakdown can result in secondary pollution by allowing organic and heavy metals to seep into groundwater and soil. Yong et al. (2019) predict that 80% of Malaysian open-dumping landfill sites will be full and require closure in the next ten years. Incineration offers a way to decrease waste volume by 80%, but it requires significant energy and financial investments (ACT enviro, 2024). Worries also exist about the release of harmful pollutants like dioxins, mercury, and lead from incinerators, which can endanger the health of nearby residents and workers with long-term exposure (Allsopp and Johnston, n.d.). Furthermore, Malaysia is currently without strict and suitable regulations for the operation of incinerators in its waste management policy and rules, which are causing worries about safeguarding public health (Sreenivasan et al., 2012).

The current sludge management methods in Malaysian WWTPs primarily rely on landfilling, posing potential risks and pollution to water and soil. Hence, Malaysia should prioritize research and planning towards adopting sustainable technologies to reduce sludge volume and mitigate environmental impacts. Despite advancements in developed countries, Malaysia lacks comprehensive policies and regulations concerning resource recovery from the water sector. The introduction of LCA studies can aid in evaluating the environmental impacts of sludge production, from its generation to its end-of-life stage. However, its application in analyzing sludge management in Malaysian WWTPs remains limited due to the absence of local life cycle inventory databases and regulation by environmental agencies. Comparative

LCA studies evaluating the environmental impacts of different sludge management methods in Malaysian treatment plants are lacking.

Moreover, only few research papers concentrate on the economic feasibility of sludge management using the Life Cycle Costing (LCC) methodology. Therefore, comprehensive LCA studies are urgently needed in Malaysia's wastewater treatment industry. These studies would enable decision-makers to prioritize solutions that minimize adverse environmental impacts and align with circular economy principles. Consequently, LCA integration is essential to assess the environmental impacts of sludge management in Malaysian WWTPs and analyze alternative disposal methods with lower environmental burdens.

1.4 Aim and Objectives

This study aims to assess the environmental impacts of municipal sludge management in Malaysia, aligning with the progress towards Sustainable Development Goals (SDGs). To achieve this goal, several objectives have been outlined as follows:

(1) To identify the life cycle inventory of sludge management using GaBi software
(2) To evaluate the environmental impact indicators of different sludge management using CML2001 methodology

1.5 Scope and Limitation of the Study

The scope of study is to evaluate the environmental impacts of various sludge management practices in Malaysia. Utilizing Life Cycle Assessment (LCA), the study aims to assess the environmental consequences of a system throughout its entire life cycle by identifying all relevant inputs and outputs. To streamline the research, some limitations have been set within the scope. Specifically, the study will not analyze wastewater treatment methods, treatment plant construction, machinery, or auxiliary equipment. The primary database utilized is sourced from the GaBi student version, referred to as a Life Cycle Inventory (LCI), which gathers relevant data and information about the system or product. The CML2001 methodology has been chosen as the Life Cycle Impact Assessment (LCIA) method to evaluate the environmental impacts of different sludge management practices, as discussed further in Chapter 2.

1.6 Contribution of the Study

LCA holds immense potential to drive positive outcomes across the environment, society, and the economy in the wastewater treatment sector for sludge management. Through its systematic approach, LCA facilitates a thorough evaluation of the environmental impacts of various sludge management, helping identify processes that minimise resource consumption and pollution. By pinpointing these sustainable pathways, LCA empowers decision-makers to choose strategies that reduce ecological footprints while safeguarding ecosystems and water resources. Moreover, the integrated use of LCA ensures that the solutions chosen align with environmental goals and cater to social welfare. This synergy promotes job creation, community engagement, and public health benefits, fostering a more inclusive and resilient society.

1.7 Outline of the Report

This study will explore the environmental implications of municipal sludge management through various disposal methods in Malaysia across five chapters.

Chapter 1: Introduction, Research Background, Problem Statements, Objectives, Scope of Work, Study Contribution, and Study Outline. This chapter aims to provide readers with a comprehensive understanding of the chosen topic and establish new insights by the study's conclusion.

Chapter 2: Literature Review on Municipal Sludge Management and LCA Framework. This chapter will review existing literature, outlining comprehensive studies on the environmental impacts of different sludge management practices. It will also discuss available technologies for sludge management, the application of LCA in assessing environmental effects, and its implementation in wastewater treatment plants.

Chapter 3: Methodology. This chapter will cover various aspects, including site selection, collection of sludge characteristics, defining the system boundary, collecting input and output data, and interpreting life cycle assessment.

Chapter 4: Results and Discussion. This chapter will present results in graphical, tabular, and other formats, followed by a transparent discussion based on the obtained results. The chapter will propose preferred disposal methods with minimal environmental impacts after comparing the system's outputs.

Chapter 5: Conclusion and Recommendations. This final chapter will summarize the study's outcomes and limitations. Recommendations for further research and improvement will be provided for future researchers to expand upon the analysis presented in this final-year project to encompass a broader scope.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter offers a summary of how sludge is handled at wastewater treatment plants (WWTP) and the environmental impacts that come with it. As the population continues to grow and by-product production rises, the disposal of sludge has become a major problem due to the increased use of municipal water. This chapter will examine the environmental effects of various sludge management techniques, such as landfilling, incineration, anaerobic digestion, land spreading, pyrolysis, and composting. This chapter also highlights current sludge management practices in Malaysia, introducing the concept of applying life cycle assessment (lca) to assess environmental impacts in the wastewater industry for resource recovery and minimizing environmental consequences. Furthermore, the chapter covers the LCA tool and database employed for a thorough evaluation of the environmental effects linked to sludge disposal.

2.2 Malaysia Sludge Management Policy

The rapid expansion of Malaysia's population has resulted in a corresponding surge in wastewater and sludge production, presenting a considerable environmental challenge. The management of sludge within wastewater treatment facilities is overseen by the National Water Services Commission (SPAN), which has outlined key objectives aimed at reducing sludge production, ensuring the production of safe and hygienic material, and promoting reuse options over disposal methods (Azman et al., n.d.). Sludge management involves the proper handling, treatment, and disposal of residual solid material generated during wastewater treatment processes. Due to its pollutant content, improper disposal of sludge can pose risks to ecosystems and water bodies, thereby endangering public health and hygiene if not managed appropriately.

Landfilling stands as Malaysia's predominant and straightforward approach to sludge disposal. However, this method requires well-dewatered sludge with good biological stability to prevent the emission of unpleasant odors. Challenges such as limited space and high construction costs are significant concerns associated with landfilling. Alternatively, leveraging sludge in agriculture and forestry as a soil amendment provides a sustainable avenue for material recovery, offering advantages in storage, transportation, and application ease. Furthermore, harnessing energy from sludge through technologies like anaerobic digestion, pyrolysis, and incineration offers effective means to mitigate environmental impacts while contributing to renewable energy generation. Methane gas produced during these processes can be captured and utilized for internal electricity generation, thereby reducing reliance on external energy sources and mitigating carbon emissions.

The Department of Environment (DOE) has put into effect regulations on sludge management, particularly with the 2010 Environmental Quality (Sewage and Industrial Effluents) Regulations. These rules are designed to deal with instructions on waste and scheduled waste management, which require compliance with specific normative measures found in documents like the Malaysian Sewerage Industry guidelines (Volume II) by the Sewerage Service Department (SPAN), DOE guidelines for selecting sites for sludge disposal, and Temporary guidelines for using biosolids as fertilizer for non-food and food crops (Spinosa, 2015).

2.3 Source of Sludge

Sludge is a semi-solid mixture which originates from various industrial processes, agricultural activities, and wastewater treatment procedures. Industrial sludge is a byproduct of operations in industries such as pulp and paper, food manufacturing, and chemical and fuel production, characterized by diverse chemical compositions. Agricultural practices like animal husbandry, crop cultivation, and food processing also contribute organic waste that forms sludge, often sourced from livestock manure and agricultural runoff residues. Sewage sludge, on the other hand, is a byproduct of wastewater treatment, comprising organic matter from human waste, food remnants, microorganisms, and inorganic solids from household products and medications (CAMBI, 2024).

Untreated wastewater presents considerable risks to human health, hygiene, the environment, and groundwater quality if discharged without proper treatment. Hence, wastewater typically undergoes a series of intricate treatment processes before being released into rivers or other water bodies. Wastewater treatment plants (WWTPs) typically comprise five consecutive stages, outlined in Figure 2.3.1. Pre-treatment is the first stage of wastewater treatment which consists of removing debris and large particles that could damage the plant or equipment during the purification process. Screens and sieves are installed at this stage to remove solid waste; subsequently, degreasers and descenders are used to remove grease and sand. Preliminary treatment is the following stage which aims to remove part of the suspended solids whereby wastewater is retained in the centrifuge for one to two hours to allow the settling of suspended particles with the help of gravity. During this process, coagulants (alum) and flocculants (lime) are added to improve the sedimentation of solids and remove phosphorus.

In third stage, secondary treatment removes organic matter from water, including nutrients like nitrogen and phosphorus. Nitrogen and phosphorus must be removed from wastewater as excessive nutrients can negatively affect water quality and ecosystem balance through eutrophication. Eutrophication is a phenomenon where algal blooms occur due to exposure to excessive nutrients. This can result in increased wastewater treatment costs, biological diversity reduction, and natural water bodies' recreational values (Wang et al., 2009). Activated sludge is the most widespread treatment to degrade and eliminate organic matter by utilizing bacteria and microorganisms. Depending on required nutrient removal, the wastewater is typically left to be treated for several days under varying oxygen conditions (aerobic, anaerobic, and anoxic). A secondary settling process usually takes place after the biological process. The biological sludge will be extracted, and purified water will flow out. Tertiary treatment is to increase the final quality of water before it is discharged back to natural river water bodies. A series of processes, including filtration with sand beds and disinfection, is carried out to eliminate pathogenic bacteria in the wastewater. Sludge treatment is a waste treatment that must be carried out before disposal. Firstly, the sludge is thickened to reduce the volume of water to be treated using an aerobic or anaerobic digestor. The process is followed by further drying the sludge with a decanter centrifuge until the sludge complies with dryness, nutrient, and pathogen content requirements. The treated sludge usually will be sent to a landfill for disposal, land application as fertilizer, or reuse in construction materials (Wang et al., 2009).

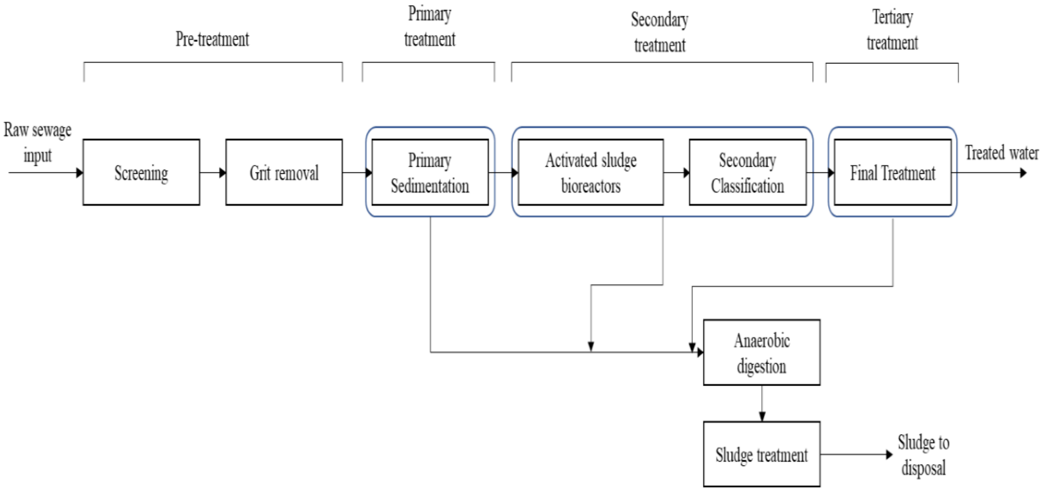


Figure 2.3.1: Overview of Typical Wastewater Treatment Process (Rashid et al., 2023)

2.3.1 Sludge Management

Sludge management in wastewater treatment involves various technologies and disposal methods aimed at handling the solid residues produced during the treatment process. The selection of appropriate sludge management and technology used depends on various factors, including sludge characteristics, regulatory requirements, and environmental considerations. The subsequent section will delve into the common technologies employed in sludge management and explore the carbon sequestration associated with various disposal methods. Table 2.3.1 below provides insights into the advantages, constraints, and carbon footprint of different sludge technology and disposal approaches.

Table 2.3.1: Advantages, constraints and carbon footprint of sludge treatment & disposal methods (Hospido et al., 2005; Champagne, 2007; Houdková et al., 2008; Singh and Agrawal, 2008; Hong et al., 2009; Sablayrolles, Gabrielle and Montrejaud-Vignoles, 2010; Lu, He and Stoffella, 2012; Lombardi et al., 2017; Li and Feng, 2018; Piippo, Lauronen and Postila, 2018; Neumann et al., 2022; BESTON, 2023; LongZhong Machinery, 2023; Yu et al., 2023; Zhao et al., 2023)

Methods	Advantages	Constraints	Carbon footprint
Landfilling	- Low investment - Simplest solution for sludge disposal	- Generate odor - Possibility to pollute underground water if not properly designed - Requires proper planning, design, operation and maintenance	592.5 to 1564 kg CO_2 eq/t DSw

Methods	**Advantages**	**Constraints**	**Carbon footprint**
Incineration	- Potential energy recovery - Volume reduction - Generated ash is stable and can be reuse for other purposes. - Minimal land required	- High technology instrumentation is required to comply with air pollution control permit - High capital investment - Potential operating problem like down time for routine maintenance which require backup - Potential for public opposition	-617 to 640kg CO_2 eq/t DS
Filter press/ belt press	- Cheap and easily available - Dewater sludge with high pressure - Consume less energy	- Produce sludge with high water content	NA
Anaerobic digestion	- Produce renewable energy and reduce use of fossil fuels - Less malodorous emission - Generate less waste	- Possible harmful substances in digestate - Limitation of season - Energy consumption to maintain digestion condition	-290 to 650kg CO_2 eq/t DS

Methods	**Advantages**	**Constraints**	**Carbon footprint**
Land application	- Replace chemical fertilizer, enhance soil fertility and promote plant growth - Improve soil structure and moisture retention - Cost effective option for soil amendment - Potential for carbon sequestration	- Potential heavy metals and pathogens might leak into soil and water bodies, posing risks to human health and environment - Potential for public opposition due to odor and aesthetic concern - Requires proper testing, monitoring, management practices - Labor intensive	-2.38 to −699 kg CO_2/yr
Composting	- Cheap - Easy operation management - Produce organic compost	- Malodorous emission - Possible pathogens in compost - Policy restriction	180 to 1100 kg CO_2 eq/t DS
Pyrolysis	- Produce energy, biochar as fuel substitution and soil conditioner - Phosphorus recovery - Less malodorous emission - Carbon sequestration	- High energy consumption - Instability of product - High operation cost	-495 to 500kg CO_2 eq/t DS

2.3.1.1 Landfilling

Landfilling stands out as one of the most commonly use methods for sludge disposal, particularly prevalent in developing nations. This approach involves burying waste underground, compacting it, and covering it with soil to prevent exposure to the environment. However, despite its widespread use, landfills significantly impact both human health and ecology and contribute to global warming. The primary source of greenhouse gas (GHG) emissions from landfills is methane. Methane emissions arise throughout the sludge treatment process, particularly when landfills are employed as the final disposal method. According to Chen and Kuo (2016), one ton of dry sludge releases approximately 60.6 kilograms of methane. Without additional stabilization treatments, landfills alone can contribute to approximately 1564 kg CO_2 eq/t DS in GHG emissions. Another study conducted by Neumann et al. (2022) on the GHG assessment of sludge management via landfills revealed methane emissions totaling 592.5 kg CO_2 eq/t DS, with one ton of dry sludge generating approximately 23 kg of methane. Overall, it's evident that sludge landfills do not present a sustainable solution in terms of GHG emissions (Zhao et al., 2023). Furthermore, Neumann et al. (2022) noted that even landfill gas recovery has minimal impact on the global warming potential of landfills.

2.3.1.2 Incineration

Incineration is a process that uses electricity to produce heat through combustion. The high temperatures in the incinerator aid in the thermal decomposition and oxidation of organic matter in the sludge. This method is effective in eliminating pathogens, minimizing odors, and reducing sludge volume, thus making disposal more convenient. Sludge is converted to ash with mineral content during the incineration process, which can then be further processed to recover valuable components like metals or phosphorus, or disposed of in designated landfills. Throughout the incineration process, the evaporation of water content as steam enables the recovery of heat from flue gas steam, which can be reused directly or converted into electrical power. There are two main methods of sludge incineration: mono-incineration and co-incineration. Mono-incineration involves burning wet or dewatered sludge in fluidized bed combustors (FBCs) at a temperature of 850 degrees Celsius, with the addition of auxiliary fuels like coal or natural gas to sustain combustion.

On the other hand, co-incineration entails burning sludge as an additional fuel in cement kilns (Yu et al., 2023). Drying wet sludge requires a significant amount of energy to remove moisture. Dewatered sludge, with a moisture content of 80-85%, typically undergoes traditional thermal drying methods to achieve a moisture content of 10-30% before incineration due to its low calorific value (Ma, Zhang and Li, 2016). The main sources of greenhouse gas (GHG) emissions in sludge incineration stem from CO_2 emissions from heavy oil, amounting to 39.8kg CO_2 eq/t DS (Tarpani and Azapagic, 2023). By implementing energy recovery, which consists of 94% electricity and 6% heat, emissions are decreased to -147kg CO_2 eq/t DS (Tarpani and Azapagic, 2023). Thermal drying incineration is responsible for the majority of GHG emissions, with 103kg CO_2 eq/t DS generated from transportation and heat for sludge drying (Zhang et al., 2019). A study conducted by Piippo, Lauronen, and Postila (2018) comparing mechanical and thermal drying methods revealed that electricity consumption and supplementary fuel significantly contribute to abiotic CO_2 GHG emissions in mechanical drying, while electricity and steam consumption are the primary contributors in thermal drying. The avoided CO_2 emissions from both methods are substantial, with mechanical drying at 942.5 kg CO_2 eq/t DS and thermal drying at -1047 kg CO_2 eq/t DS. Furthermore, utilizing dry sludge as fuel in power plants aids in reducing CO_2 emissions from fossil fuels. In general, GHG emissions from sludge incineration range from -617 to 640 kg CO_2 eq/t DS, influenced by the drying method, auxiliary fuel usage, and energy recovery (Houdková et al., 2008; Hong et al., 2009; Lombardi et al., 2017).

2.3.1.3 Anaerobic Digestion

Anaerobic digestion (AD) is a biochemical process that transforms organic substances from sewage into useful commodities like biogas, biochar, and liquid fertilizer. It has gained popularity in WWTPs for sludge stabilization because of its cost-effectiveness and efficient carbon recovery for renewable biogas fuel (Achinas and Euverink, 2020). This procedure happens without oxygen, aiding in the breakdown of microorganisms. Anaerobic digestion can occur in reactors designed for specific site and feedstock conditions at either mesophilic or thermophilic temperatures. While undergoing anaerobic digestion, waste decomposes into biogas, mainly consisting of CO_2, CH_4, and minimal amounts of other gases (Yan et al., 2021). Multiple steps in the procedure require the utilization of electricity, such as anaerobic digestion, belt filter dewatering and storage, and agricultural uses. The biogas produced helps maintain the digester environment, with any extra biogas being used to generate electricity (Yu et al., 2023).

Li and Feng (2018) carried out a study comparing the life cycle impact assessment (LCIA) and energy efficiency of anaerobic digestion and pyrolysis processes. Li and Feng (2018) reported that in their research, AD used 2.8 GJ of heat and 50 kWh of electricity per ton of dry solids, while pyrolysis used 2940 MJ of heat and 40 kWh of electricity per ton of water. Research conducted by Piippo, Lauronen, and Postila (2018) found that the greenhouse gas emissions from anaerobic digestion were measured at 141.15 kg CO_2 eq/t DS, which decreased to -341.3 kg CO2 eq/t DS when excluding biological CO_2. Biogas usage in combined heat and power systems leads to the production of biological CO_2, while abiotic CO_2 is formed during anaerobic digestion. Replacing fertilizer with compost results in even lower emissions, bringing the level down to -565.7 kg CO_2 eq/t DS as shown in Piippo, Lauronen, and Postila's 2018 study. GHG emissions associated with anaerobic digestion and agricultural use range from -290 to 650 kg CO_2 equivalent per ton of dry solids, depending on factors such as treatment parameters, electricity production, and replacement of fertilizers (Yu et al., 2023).

2.3.1.4 Land Application

Applying sewage sludge to land is a sustainable option instead of sending it to landfills, which helps reduce carbon emissions from waste. This technique improves soil by adding organic material and necessary nutrients such as carbon, nitrogen, phosphorus, potassium, sulfur, copper, and zinc (Pavan Fernandes, Bettiol and Cerri, 2005; Singh and Agrawal, 2008), leading to improved soil quality and decreased need for synthetic fertilizers. Land use has the potential to store carbon, which helps in preserving soil carbon sinks and can lead to earning carbon credits (Singh and Agrawal, 2008). Studies indicate that applying compost can lead to the storage of 8% compost carbon in the long run, with significant potential for carbon sequestration equal to CO_2 eq/dry Mg wastewater solids (Recycled Organics Unit, 2006). Nevertheless, research conducted by Lundin et al. (2004) shows that even though sewage sludge can replace mineral fertilizers, the energy required for pasteurization, transportation, and spreading could result in heightened CO_2 and N_2O emissions when applied to land. Pilli et al. (2014) showed that the nutrient levels in sewage sludge affect the success of GHG reductions from carbon sequestration, with higher nutrient content leading to increased carbon sequestration rates of -2.38 Mg CO_2/yr. Low nutrient concentration sludge shows decreased levels of carbon sequestration at around -2.38 Mg CO_2/yr. Under high nutrient levels, applying sewage sludge on land can greatly decrease emissions, proving to be a cost-efficient choice due to its fertilizing properties (Champagne, 2007; Singh and Agrawal, 2008; Lu, He and Stoffella, 2012).

2.3.1.5 Composting

Utilizing sewage sludge for composting offers a sustainable method for recovering nutrients, making use of its valuable organic material and important nutrients that are beneficial for soil and plants. Compost is appealing because its phosphorus levels can be used as a substitute for fertilizers in equal amounts (Lanno et al., 2021). Zhuang et al. (2022) stated that the composting starts with thickened sewage sludge being dewatered initially, reaching around 27% total solids (TS) with centrifuge technology. The drained sludge is mixed with a bulking agent, thoroughly stirred, and moved to windrows for regulated composting. The compost product is used in agricultural areas. Decomposing large amounts of organic carbon in compost stabilizes and improves soil humus content. Humus plays a vital role in soil, contributing to its spongy texture and improving water retention capabilities (Costa et al., 2022). Research indicates that it is crucial to add bulking agents such as cattle manure and sawdust in order to regulate the moisture levels of the soil and improve the exchange of air and water within the composting material (Ma et al., 2019).

Composting is a process that requires oxygen and breaks down organic carbon to turn it into carbon dioxide (CO2). According to Yu et al. (2023) research findings, methane gas is produced as a byproduct in the anaerobic process, releasing around one percent of the original carbon content of sludge into the air. Nitrous oxide, also known as N_2O, produces approximately 0.5% - 5% of the original nitrogen content in composting processes (Yu et al., 2023). Most of the energy used in composting comes from running the mixer and conveyor. This requires about 33.2 kWh per ton of dry solids for mixing, and 501 kWh/t DS for fermentation and maturation. (Tarpani et al., 2020). Scientists studied the environmental effects of utilizing composted sludge, finding that composted sludge results in 197 kg CO_2 eq/t DS of greenhouse gas emissions. During the composting process, the significant contributors to GHG emissions are CH_4 from sludge composting and CO_2 from electricity consumption. A credit of minus 19.54% is attributed to composting for displacing chemical fertilizers, which leads to a decrease in CO_2 emissions during their production (Yu et al., 2023). Furthermore, research conducted by Lishan et al. (2018) shows CO2 equivalent emissions of 1097.9 kg CO_2 eq per ton of dry substance during the disposal phase. Differences in greenhouse gas emissions during composting can vary from 180 to 1100 kg CO_2 equivalent per ton of dry substance, based on the characteristics of the electricity grid and various composting methods as cited by Hong et al. (2009), Sablayrolles, Gabrielle, and Montrejaud-Vignoles (2010), and Lombardi et al. (2017).

2.3.1.6 Pyrolysis

Pyrolysis, a thermal degradation process, is conducted in the absence of air and converts waste into valuable products at high temperatures ranging from 300 to 1300°C (Devi and Rawat, 2020). This technique enables the thermal breakdown of sludge, resulting in the formation of solid biochar, gaseous byproducts such as carbon monoxide, methane, hydrogen, and carbon dioxide, and liquid outputs known as bio-oil (Yu et al., 2023). Biochar, a carbon-rich substance, acts as a soil enhancer, improving fertility and sequestering carbon, while bio-oil is utilized as a fuel source for engines, electricity generation, and heat production in power plants. Nevertheless, the implementation of pyrolysis necessitates specialized equipment and expertise, leading to substantial capital investment and operational expenses. The distribution of product phases is influenced by the quality of the sludge, with bio-oil and gas production increasing in correlation with volatile solids (VS) and moisture content (Xu, Chen and Hong, 2014).

Electricity consumption plays a crucial role in various stages of pyrolysis, including filter press operation, thermal drying, and the pyrolysis process itself. Around 115 to 230 kg of biochar, 20 to 40 kg of bio-oil, and 2.1 to 4.2 kW of heat can be obtained from pyrolysis gas, with reactor operation and accessory devices requiring approximately 77.78 kWh/t DS of electricity (Tarpani and Azapagic, 2023). Natural gas is used as an additional energy source for dried sludge containing 60% moisture, and the amount of energy consumed depends on the organic material and pyrolysis parameters. In terms of greenhouse gas emissions, pyrolysis accounts for around 315 kg of CO_2 equivalent per ton of dry substance, with a large portion linked to gas usage during thermal drying. Nevertheless, the use of pyrolysis gas, biochar, and bio-oil effectively decreases greenhouse gas emissions, leading to a decrease of -251 kg CO_2 eq/t DS by avoiding the use of heat and fuel. Research conducted by Barry et al. (2019) reveals different options for using biochar, showing that burning biochar without recovering energy results in greenhouse gas emissions of 646.98 kg CO_2 eq/t DS. Conversely, using biochar in fuel and agricultural practices can lower greenhouse gas emissions, with a range of -495 to 500 kg CO_2 eq/t DS. By utilizing pyrolysis to recycle energy, decreasing the use of fossil fuels, substituting mineral fertilizers, and storing carbon in biochar, it is possible to significantly reduce greenhouse gas emissions (Hospido et al., 2005; Houdková et al., 2008).

2.3.2 Existing Sludge Treatment & Disposal Route in Malaysia

Based on the Environmental Quality (Scheduled Waste) Regulations 2005, DOE classifies sludge produced from WWTPs as scheduled water, mandating its disposal at prescribed premises only in Peninsular Malaysia. Since 1994, wastewater management in Malaysia has been primarily handled by a private company, Indah Water Konsortium (IWK) Sdn Bhd, which operates and maintains sewer networks, treatment plants, and pump stations. Common methods of sewage sludge management in Malaysia include landfilling, mechanical dewatering, land application as fertilizer, and anaerobic digestion.

Notably, three modern WWTPs equipped with anaerobic digestion facilities are operational: Jelutong WWTP in Penang, Pantai WWTP in Kuala Lumpur, and Langat WWTP in Selangor (Indah Water, 2016). Pantai 2 WWTP, already operational, has been designed to produce a substantial amount of biogas (9,600 m3/d). By 2018, it successfully generated about 450-500 kW of electricity from the produced biogas (Indah Water Konsortium, n.d.). Langat 2 WWTP, the largest in Malaysia, is designed to treat 1,130,000 m3/d of water and is operated by Pengurusan Aset Air Berhad (PAAB). Jelutong WWTP, on the other hand, has the capacity to handle wastewater from 800,000 population equivalents (PE). Despite significant annual production of sewage sludge in Malaysia, the predominant method of sludge treatment remains landfilling after employing dewatering techniques such as filter press, belt press, and centrifuge. According to the 2022 sustainable report by Indah Water Konsortium (2022), collaborations with experts and universities have been initiated to explore sustainable practices, including utilizing treated sludge as fertilizer for rubber plantations, employing sludge and food waste as feedstock for breeding black soldier fly larvae (BSFL), and producing clay bricks and biofuels using sludge.

2.4 Environmental footprint & its importance

The environmental footprint is a thorough assessment of the impact human activities have on the environment, including resource usage, waste production, and emissions discharge during a product or process's entire life cycle. It assesses different effects like carbon, water, land, and air footprints, offering guidance on ways to decrease environmental impacts (Čuček, Klemeš, and Kravanja, 2015). Various sludge disposal techniques result in substantial carbon footprints and environmental consequences. One common method of waste disposal, landfilling, releases significant amounts of methane, a potent greenhouse gas, during anaerobic decomposition. Incineration decreases the amount of sludge and harmful microorganisms, but also emits carbon dioxide and other contaminants, leading to climate change and air pollution. Anaerobic digestion collects biogas for energy production, decreasing dependence on fossil fuels and providing a greener alternative. Land application and composting offer chances for storing carbon in soil, improving soil fertility and reducing climate change impacts. Improperly handling may cause nutrient runoff and water pollution, negating their positive environmental effects. While pyrolysis can successfully transform sludge into biochar for improving soil quality and trapping carbon dioxide, careful management of emissions and energy input is needed to reduce its impact on the environment. Overall, the decision on how to manage sludge has a major effect on both carbon emissions and environmental results, underlining the significance of factoring sustainability into waste management approaches.

2.5 Methods to estimate environmental footprint

Different techniques have been created to measure and evaluate the environmental impact linked to items and procedures, such as Life Cycle Assessment (LCA), simplified LCA, checklist methods, and Material, Energy, and Toxicity (MET) evaluations. These techniques are designed to tackle the environmental impacts of human actions, promote well-informed decision-making, and encourage sustainable practices.

LCA is a comprehensive method that evaluates the environmental impacts of a product or process throughout its entire life cycle, including raw material extraction and end-of-life disposal. It takes into account phases like production, shipping, consumption, and ultimate disposal, evaluating environmental factors including energy use, water consumption, greenhouse gas emissions, and depletion of resources. The ISO 14040 standard offers a structured framework for performing LCA assessments.

Simplified LCA offers a streamlined approach to assessing environmental footprints while maintaining impact assessment accuracy. It focuses on evaluating environmental impacts throughout a product's lifecycle with a narrower scope and reduced complexity compared to traditional LCA. This enables quicker and more resource-efficient estimation of environmental impacts.

The checklist approach involves identifying and evaluating specific environmental impacts through a predefined checklist, providing a quick and practical tool for initial environmental assessment. While it does not offer a comprehensive LCA analysis, it supports decision-making, raises awareness, and identifies improvement areas.

The MET Matrix stands for Material, Energy and Toxicity assessments which assesses environmental impacts based on material composition, energy consumption, and toxicity potential throughout a product's life cycle. It serves as a valuable tool during the design phase, providing both qualitative and quantitative assessments across five main life cycle stages.

Among these methodologies, LCA is widely used by researchers and industries for evaluating environmental impacts and sustainability. It offers a comprehensive framework, from goal and scope definition to interpretation, providing quantitative information based on objective methods. However, it requires skilled experts and involves complex processes compared to qualitative information.

2.6 Life Cycle Assessment (LCA)

LCA is a systematic approach employed to evaluate the environmental impacts of a product or process from the moment raw materials are obtained to when it is disposed of. This all-encompassing method is alternatively referred to as 'cradle to grave'. ISO has created a structure for performing LCA research, particularly with guidelines like ISO 14040 and ISO 14044 released in 2006. The four main stages of LCA studies are outlined in ISO 14040 as goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and life cycle interpretation (ISO14040, 2006). The connection between these four stages is shown in the diagram in Figure 2.6.

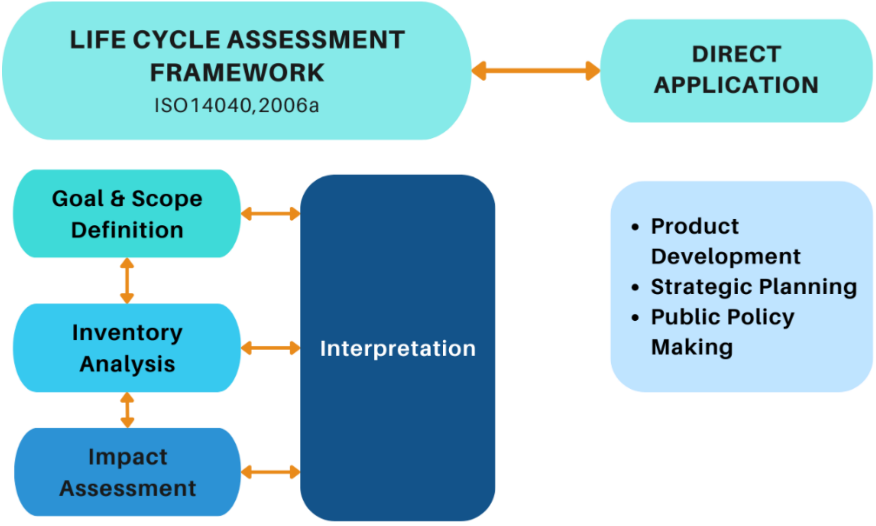


Figure 2.6: Phases of an LCA (ISO14040, 2006)

2.6.1 Goal & Scope of LCA

During the first stage of LCA, it is essential to establish the objective and boundaries. This includes defining the purpose of the assessment, such as who it is for and how it will be used. In addition, defining the scope indicates the assessment's range and encompasses important components like the product system and its purpose. This involves recognizing both processes that come before and after, such as production, distribution, usage, and disposal of materials. The functional unit is essential for converting LCA results into understandable terms and serves as the basis for measurement in the system. System boundaries dictate which elements of the system are considered or disregarded during evaluation, aiding in defining the scope of the analysis. Moreover, the process of determining the impact type and assessment method includes pinpointing the environmental impact categories to be assessed and the approach for evaluating these impacts. Setting standards for the quality and dependability of data in the evaluation ensures precision and trustworthiness of findings, while openly acknowledging any assumptions and constraints is crucial for the study's integrity.

2.6.2 Life Cycle Inventory Analysis

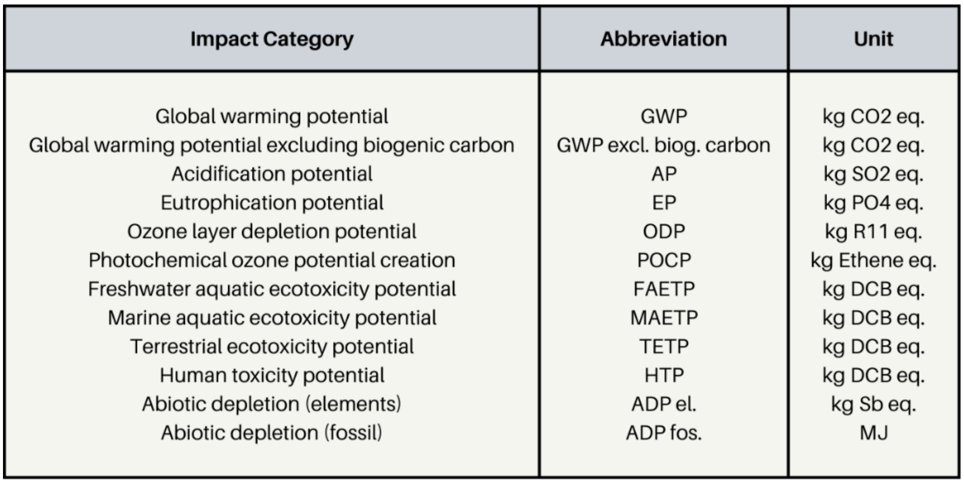
In the second stage of LCA, called life cycle inventory analysis (LCI), the focus turns to gathering data and performing calculations to measure the inputs and outputs of materials and energy in the product system being studied. This requires collecting information from different sources, beginning with the most important unit operations and then moving on to less important ones. Inputs typically include raw materials and energy consumption, while outputs consist of disposal methods and emissions to air, water, and land, taking into account legal limits for discharge. In order to simplify the process of collecting data, various software tools like SimaPro, GaBi, and OpenLCA can be used to help gather inventory data linked to background systems. These instruments improve effectiveness and precision in LCI compilation, making it easier to conduct a thorough analysis of the product's life cycle.to background systems.

2.6.3 Life Cycle Impact Assessment

During the third stage of LCA, known as LCIA, focus shifts to assessing the possible environmental effects of the production system using data from the LCI. LCIA deals with different environmental concerns like energy usage, global warming, and water contamination, providing a thorough grasp of the system's environmental impact. This stage involves four important components: categorization, description, standardization, and prioritization. Classification entails organizing the inputs and outputs in LCI results according to their expected environmental effects, while characterization involves adding up the data in impact groups using equivalency factors. Characterization is essential for ensuring that each model is in line with scientific understanding. LCIA utilizes two primary methods for representing characterization: midpoint and endpoint. The midpoint method looks at environmental impacts in between various stages of cause and effect, while the endpoint method considers the ultimate effects of pollution on human health, ecosystems, and resources (Dong et al., 2021). Normalization is the process of dividing the characterization value of an impact category in a product system, making error checking and interpretation easier. Weighting consists of giving importance to impact categories relatively, assisting in decision-making processes. Different LCIA methods like CML 2001, ReCiPe, IMPACT 2002+, and the Eco-indicator method are used to calculate different life cycle impact indicators, allowing for the choice of suitable methods for specific impact categories. Even though midpoint LCIA methods are frequently utilized in LCA studies, the endpoint approach is perceived as being less clear and dependable.

2.6.4 CML method

The CML method stands out as a prominent LCA methodology employed in impact assessment, originating from researchers at the University of Leiden in the Netherlands in 2001. This method covers a wide spectrum of over 1700 flows. It integrates characterization techniques and impact categories crucial for assessing environmental consequences. While lacking in weighting, it does support normalization. The CML method adopts a problem-oriented midpoint perspective, offering a comprehensive catalog of essential impact categories commonly utilized in LCAs. This CML method utilize midpoint indicators, as depicted in diagram 2.6.4 below.



Impact Category	Abbreviation	Unit
Global warming potential	GWP	kg CO2 eq.
Global warming potential excluding biogenic carbon	GWP excl. biog. carbon	kg CO2 eq.
Acidification potential	AP	kg SO2 eq.
Eutrophication potential	EP	kg PO4 eq.
Ozone layer depletion potential	ODP	kg R11 eq.
Photochemical ozone potential creation	POCP	kg Ethene eq.
Freshwater aquatic ecotoxicity potential	FAETP	kg DCB eq.
Marine aquatic ecotoxicity potential	MAETP	kg DCB eq.
Terrestrial ecotoxicity potential	TETP	kg DCB eq.
Human toxicity potential	HTP	kg DCB eq.
Abiotic depletion (elements)	ADP el.	kg Sb eq.
Abiotic depletion (fossil)	ADP fos.	MJ

Figure 2.6.4: Impact categories of CML2001 method (ISO14040, 2006)

2.6.5 ReCiPe method

ReCiPe 2016 is an updated form of the ReCiPe 2008 methodology for impact assessment. The Dutch National Institute for Public Health and the Environment (RIVM), Radboud University Nijmegen, Norwegian University of Science and Technology, and PRé Sustainability worked together to develop it. This enhanced method merges the midpoint approach from CML 2001 with the damage pathways specified in Eco-indicator 99 (Catalán and Sánchez, 2020). ReCiPe 2016 brings in midpoint and endpoint indicators to convert Life Cycle Inventory (LCI) data into a brief collection of life cycle impact assessment results. The framework includes eighteen midpoint categories that concentrate on problem-oriented aspects, with the goal of expressing the worldwide scale of characterization factors. Moreover, it consists of three different endpoint classifications focusing on harmful elements, categorized as human health, ecosystems, and resource availability. The image below illustrates how midpoint impact categories, damage pathways, and endpoint areas of protection are interconnected, representing the core concept of ReCiPe 2016.

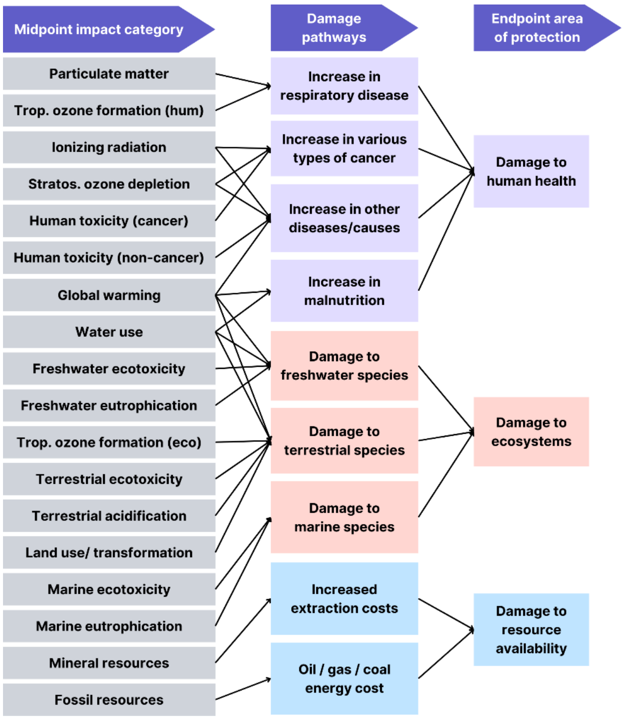


Figure 2.6.5: Overview of impact categories covered in ReCiPe 2016 methodology and their relation to areas of protection (RIVM, 2018)

2.6.6 Life Cycle Interpretation

The life cycle interpretation is the final step of the LCA process, analysing, calculating, and organizing the results from the LCI and LCIA. During this phase, the LCA professional recognizes key environmental factors, their effects, and the individual processes in the life cycle. Sensitivity analysis is done to check the reliability of the findings, then scenario analysis and data quality review are carried out to verify alignment with the study's goals. Conclusions are made and suggestions are given to improve the LCA study, based on the analysis. The selection of LCA software is crucial as it has a major impact on the results of the evaluation. The software package's quality is judged by its capacity to follow set standards and proficiently handle different outputs.

2.6.7 LCA Tools & Database

LCA tools are software programs created to evaluate the environmental effects of products throughout different points in their life cycles. These tools provide functions like data entry, assessment techniques, and reporting abilities, allowing users to analyze various scenarios and calculate environmental effects using provided data. Conversely, an LCA database contains information regarding the environmental effects of various materials, processes, and actions. This comprises measurements like energy usage, emissions of greenhouse gases, water consumption, and additional ecological factors. Effective LCA tools and databases enable professionals to collect necessary information for their evaluations, guaranteeing that their analyses are thorough and precise. Table 2.6.7.1 below presents the various LCA software options on the market, outlining their benefits and drawbacks. At the same time, Table 2.6.7.2 provides details on current LCA databases, such as their main sources of data, geographic coverage, and notable characteristics.

Diogo et al. (2017) evaluated several LCA software tools like GaBi, SimaPro, Umberto, and OpenLCA, considering aspects such as functionality, flexibility, database quality, user-friendliness, and service support. The results showed that GaBi excelled in functionality, ease of use, and quality of service, whereas SimaPro was identified as the most economical choice. Yet, for professionals looking to reduce expenses on investments, OpenLCA has become an attractive option for performing life cycle assessment studies. When focusing on wastewater treatment plants, SimaPro, GaBi, and OpenLCA are the most common software tools for LCA analysis, providing specific features and databases designed for wastewater treatment processes. As a result, GaBi was chosen as the favored LCA tool for assessing sludge management in Malaysia's wastewater treatment facilities.

Table 2.6.7.1: Overview of LCA software available (Diogo et al., 2017; Market Research Report, 2022; Altermaker, n.d.; GaBi, n.d.; Hillege, 2023; One Click LCA, n.d.; OpenLCA, n.d.; SimaPro, n.d.; Umberto, n.d.; USEtox, n.d.)

LCA Software	Developer	Advantages	Limitations	Exceptional Field
Ecodesign Studio	Altermaker	Comply with ISO 14040 standard Able to identify origins of impacts, hotspot Support LCA analysis, manage bills of material, launch redesign simulations Carry out environmental assessment of a product	High cost investment	Product Design, Product Management, Sustainability Management
Ecochain Mobius	Ecochain Technologies B.V., Netherlands	Comply with ISO 14040 standard Support LCIA analysis Cloud based software to share & store data Integrated with Ecoinvent, NMD databases Able to compare two product LCAs with different environmental impact categories Results can be exported to Excel, pdf Able to generate graphs, charts & tables for impact analysis & hotspot	High cost investment	R&D, Product Design, Product Management, Engineering, QHSE, and Sustainability Management
GaBi	IKP Uni,	Comply with ISO 14040 standard	High cost investment	All industries

LCA Software	Developer	Advantages	Limitations	Exceptional Field
	Stuttgart/PE, Germany	Support LCIA analysis, Monte Carlo uncertainty & sensitivity results, social & cost modelling	Most of the datasets are aggregated	
		Sankey diagram & bar charts are used to show LCA results		
		Inventory analysis uses tables & automatic flow balances		
		Professional database with datasets & extension databases		
One Click LCA	One Click LCA, Finland	Comply with green building certification schemes like LEED, DGNB and BREEAM	High cost investment	Construction sectors
		Provide modelling & reporting features for building materials/construction products		
		Analyse energy & water consumption of buildings, embodied carbon emission, environmental impacts of construction projects		
		Support LCA, LCC analysis		
		Integrated with Revit, BIM		
		Cloud based software to share & store data		

LCA Software	Developer	Advantages	Limitations	Exceptional Field
OpenLCA	GreenDelta GmbH	Free for users and open source	Not comply with ISO 14040 standard	All industries involved products' production process & inputs
		Sankey diagram & bar charts are used to show LCA results	No LCIA, analysis, uncertainty & sensitivity results	
		Inventory analysis displayed in table	Lack of datasets freely available	
			Normalization & weighting factors are not available for ILCD/PEF method	
SimaPro	Pre-Consultants, Netherlands	Comply with ISO 14040 standard	High cost investment	All industries involved products' production process & inputs
		Support LCIA analysis, monte Carlo uncertainty & sensitivity results, social modelling	Limited number of datasets format	
		Sankey diagram & bar charts are used to show LCA results		
		Tables & automatic flow balances are used for inventory analysis		
		Integrated with ecoinvent database		
		Most of the datasets are unit processes		

LCA Software	Developer	Advantages	Limitations	Exceptional Field
Umberto	iPoint, Germany	Sankey diagram & bar charts are used to show LCA results	High cost investment	All industries involved products' production process & inputs
		Inventory analysis presented in table form	No Monte Carlo analysis & uncertainty analysis	
		Results can be exported to Excel Pivot Table & Dashboard Chart	Normalization & weighting factors are not available	
		Excel based tools for sensitivity analysis	Unable to import/export datasets to traditional LCA formats	
		Ecoinvent database and/or GaBi database are integrated in study		
		Support cost modelling, Material Flows Analysis		
USES-LCA	USETOX model	Tool for LCA, foot printing, risk screening, and chemical substitution	Only carry out chemical risk assessment & LCIA model analysis	Chemical manufacturing, products production, chemical management, pharmaceuticals, pesticides, textile, plastics & polymers
		Able to assess human toxicological and 17 ecotoxicological impacts in LCA		
		Comprehensive database		
		Able to evaluate social & economic impacts of products		

Table 2.6.7.2: LCA databases (Takano et al., 2014; Blonk Sustainability, 2023; iPoint, 2023)

Databases	**Developer**	**Primary data source**	**Geographical Representativeness**	**Exceptional Field**
GaBi database	Sphera	Industrial data, literature data, other database (ELCD, IBU, etc.)	Germany or Europe	Product production and industry sectors
Carbon Minds	Carbon Minds GmbH	Industrial data, trade data	China, US, Germany, Belgium, Europe average, Netherlands, Global average	Chemicals and plastic industry
Ecoinvent	Swiss Centre for Life Cycle Inventories	Industrial data, literature data	Switzerland or Europe	Product production and industry sectors
Agri-footprint	Blonk	Industrial data, literature data, other database (FAO, ecoinvent	Belgium, Brazil, China, Denmark, Germany, Spain, Netherlands, New Zealand, Europe, UK, US	Agriculture, fisheries & food sectors

Databases	**Developer**	**Primary data source**	**Geographical Representativeness**	**Exceptional Field**
USLCI	NREL	Industrial data, literature data	US	Building materials & construction sectors
IBO	IBO Austrian Institute for Health and Ecological Building GmbH	Industrial data, literature data, other database (ecoinvent, etc.)	Austria and neighbouring countries	Building materials & construction sectors
CFP	Japan Environmental Management Aassociation for Industry/Advanced Industrial Science and Technology	Statistic data, literature data	Japan	Product production and industry sectors
Synergia	Finnish Institute of Environment	Industrial data, literature data	Finland	Product production and industry sectors

2.7 LCA Application in Wastewater Treatment Plant

Conventional wastewater treatment plants commonly depend on electricity for pumping and aeration, in addition to using chemical additives to improve nutrient removal and efficiently dewater sludge. Nevertheless, these actions may lead to negative consequences on the environment including eutrophication, acidification, and the release of greenhouse gases such as carbon dioxide, methane, and nitrous oxide, creating sustainability issues and ecological damage. Life cycle assessment (LCA) is seen as a useful tool for assessing both the environmental and economic implications of wastewater treatment systems in light of these challenges. Through the examination of crucial environmental locations throughout the complete lifespan of WWTPs, LCA empowers stakeholders to pinpoint and prioritize regions for enhancement, resulting in enhanced and more eco-friendly wastewater treatment methods. Research conducted worldwide has shown that LCA is effective in guiding actions to reduce environmental impacts, such as upgrading treatment infrastructure, enforcing stricter discharge standards, and optimizing sludge management practices. Table 2.7.1 gathers important studies that use LCA tools like GaBi, SimaPro, and USES-LCA, offering valuable information on how LCA is used in WWTPs and various sectors. In general, utilizing LCA analysis enables industry participants to make educated choices, lower their carbon emissions, and improve operational effectiveness in the long run.

A study from Piao and Kim (2016) compared the environmental effects of two major WWTPs in Korea, specifically looking at global warming potential (GWP) and human toxicity potential (HTP). The study separated the WWTPs into five parts: treating wastewater, treating sludge, burning biogas, releasing effluent, and disposing of sludge. Findings showed notable distinctions between the two WWTPs due to differences in unit processes and compositions. More precisely, for WWTP-S, the electricity generated from the wastewater line comprised 47.50% of GWP and 27.80% of HTP, with electricity from the sludge line contributing 42.79% of GWP and 25.05% of HTP. The combustion of biogas, treatment of wastewater, and disposal of sludge also had noticeable effects. The research emphasized the crucial role of nutrient removal rates, specifically phosphorus, BOD, and COD, in determining GWP and HTP in WWTPs. Furthermore, there were smaller contributions from power generation and pharmaceutical manufacturing that were noted. These results highlight the importance of including these factors in the operation and decision-making processes of wastewater treatment plants to reduce environmental impact and enhance sustainability.

In another study by Lishan et al. (2018) on wastewater treatment plants in China, hydrothermal-pyrolysis technology (HPT) emerged as a favorable method for sludge management due to its superior environmental and economic performance compared to conventional methods like incineration, landfill, and composting. Optimal proportions for sludge disposal in Xiamen were identified as 9.3% for landfill, 35.9% for incineration with 80% water content, 28.9% for HPT, and 25.9% for composting. In summary, through LCA studies, significant environmental hotspots can be identified, aiding in the development of more sustainable wastewater treatment plant processes. Research conducted worldwide has shown promising results in reducing environmental impacts by upgrading treatment methods and improving sludge disposal routes.

Table 2.7.1: Overview of Journal Paper using LCA software (Hong et al., 2009; Niero et al., 2014; Piao and Kim, 2016; Lishan et al., 2018; Zhang et al., 2019; Avató and Mannheim, 2022; Zhou et al., 2022; Drosou, Kekes and Boukouvalas, 2023; Galusnyak et al., 2023; Jain et al., 2023; Mannheim and Kruszelnicka, 2023)

Author	Year	Country	Findings	Assumptions & Limitations	LCIA Tools	Category
Avató J, Mannheim V	2022	Hungary	Landfilling of food waste contributes the highest values for GWP (37%), POCP (22%), MAETP (21%), EP (9%) and ADPF (5%) and the lowest values for AP (2%) and ADPE (0.01%)	Not account for soil carbon accumulation (uptake) Environmental impacts related to waste collection and transport are not included	GaBi	Cooking
Boukouvalas C, Drosou F & Kekes T	2023	Greece	The use of PEF processing, membrane bioreactors, UV treatment, anaerobic digestion, and thickening of digestate leads to a notable 66.73% decrease in greenhouse gas emissions in comparison to sending waste to a landfill. The implementation of PEF, MBRs, anaerobic digestion, and UV treatment resulted in decreased freshwater usage and freshwater ecotoxicity by 89.79% and 64.56%, respectively.	The data utilized are derived from reviews of literature. May not fully represent the present situation	GaBi	Canned food industry

Author	Year	Country	Findings	Assumptions & Limitations	LCIA Tools	Category
Niero M, Pizzol M, Brunn H, et al.	2014	Denmark	For climate change and depletion of fossil resources, environmental impact of aerobic sludge digestion varies depending on the category considered. For categories related to eutrophication and toxicity, plants employing anaerobic digestion followed by sludge incineration exhibit higher environmental impacts For climate change and fossil resource depletion, centralized WWTPs featuring anaerobic sludge digestion demonstrate superior performance compared to medium-sized WWTPs that utilize aerobic stabilization methods for sludge treatment.	Insufficient research focused on quantifying the fraction of bioavailable phosphorus necessary for calculating the fertilizer substitution rate.	SimaPro	WWTP
Chisalita D, Galusnyak S, Petrescu L, et.al	2023	Italy	Enhanced CO_2 resistance in bio-methanol production from wooden biomass leads to the lowest GHG emissions and GWP impact, measuring at 1288.04 kg CO_2 eq./tMeOH. Bio-methanol production from spent olive pomace with improved carbon dioxide tolerance shows the highest negative effects on the environment, generating 2511.22 kg CO_2 eq./tMeOH.	The research does not take into account the building and dismantling of the facility, repairing and maintaining operations, infrastructure, human activities related to work duties, or rare occurrences.	GaBi	biomethanol production

Author	**Year**	**Country**	**Findings**	**Assumptions & Limitations**	**LCIA Tools**	**Category**
Hong J, Hong J, Otaki M et.al	2008	Japan	The GWP values of the scenarios vary between 625.4 to 1600 kg-CO2/t-DS, with or without digestion. The best approaches for both environmental and economic advantages are thickening & melting (TM) and thickening, incineration, melting (TIM).	The expenses for incineration and agricultural application are \$402 per ton of dry solids and \$109 per ton of dry solids (calculated using a currency exchange rate of 0.16 SEK/\$), respectively.	USES-LCA	WWTP
Kim Y and Piao W	2016	Korea	The main source of global warming emissions is energy consumption, making up 90.29% of the total emissions at 22,902.55 kg CO_2 eq. Electricity usage in the sludge treatment section makes up 42.79% of energy consumption, whereas burning biogas in the cogeneration engine is a smaller part at 2.09%, equal to 1,120 kg of CO_2 emissions. Additional factors that contribute are wastewater treatment at 1,000 kg CO_2 eq and sludge disposal at 3,060 kg CO_2 eq, while incineration plays a minimal role in CO_2 emissions.	The potential environmental effects evaluation only looks at chemical substances, emissions from sludge disposal and electricity generation, and import-export statistics.	GaBi	WWTP

Author	Year	Country	Findings	Assumptions & Limitations	LCIA Tools	Category
Kruszelnicka W, Mannheim V	2023	Hungary	Marine toxicity, depletion of fossil resources, and climate change have more significant effects on the environment. Material resources and electricity used for grinding and sieving, as well as diesel usage for transport in stirred media mills, greatly affect emissions in laboratory mill life cycles.	Equipment and machinery as relevant factors are not considered in the study.	GaBi	Wet grinding process of pumice
Lishan X, Tao L, Yin W, et.al	2018	China	The composting procedure produces about 1097.9 kilograms of CO2 equivalent per every metric ton of dry sludge. High-pressure thermal hydrolysis (HPT) generates 1935 kg CO2 equivalent for every dry ton of sludge, with a payback period of 6 years when discounted. HPT shows advantages in terms of environmental efficacy, societal approval, and financial feasibility when weighing the trade-offs. Less than 0.5% of total CO2-eq emissions related to climate change are attributed to transportation. In the process of incineration, 11.8% of the total CO2-eq emissions are accounted for by the energy recovery rate.	It was assumed that the power-grid mix would reflect the national electricity mix. Transporting materials was not considered in the analysis.	GaBi	WWTP

Author	Year	Country	Findings	Assumptions & Limitations	LCIA Tools	Category
Rigamonti L, Visigalli S, Zhang H, et.al	2018	Italy	GHG emissions from incineration with mechanical drying are 1002.7 kg CO2-eq/t DS, compared to 924.01 kg CO2-eq/t DS for incineration with thermal drying. Yet, incineration with mechanical drying results in net GHG emissions of -617.7 kg CO2-eq/t DS, while thermal drying produces -874.7 kg CO2-eq/t DS.	There is limited data available to support the effectiveness of EDW in reducing contaminants such as micropollutants and pathogens.	SimaPro	WWTP
Wang D, Wei L, Zhou H, et al.	2022	China	Applying anaerobically digested sludge to soil may lead to heavy metal contamination. Incorporating passivators such as clay minerals, carbon materials, and industrial waste can solidify and stabilize heavy metals in sludge during aerobic digestion. Co-incineration has carbon emissions of -27.26 kg CO2 eq/t DS, while anaerobic digestion and anaerobic digestion with thermal hydrolysis produce emissions of -572.44 kg CO2 eq/t DS and -474.92 kg CO2 eq/t DS, correspondingly.	The research viewed carbon dioxide produced during sludge treatment and disposal as having no net impact on the environment. The study's findings on the toxicity impact are limited and require additional investigation.	SimaPro	WWTP

2.8 Limitations of LCA

LCA provides valuable insights into the sustainability of product life cycles. However, there are some limitations, especially when applied to complex and dynamic systems. One significant challenge lies in defining the scope and boundaries of the system under study. Decisions regarding life cycle stages, processes, and impacts can significantly influence study outcomes. Varying interpretations of scope may yield different results, potentially leading to misleading cross-study comparisons. Another limitation is the accuracy and relevance of the data used in LCA results. Outdated, incomplete, or inaccurate data can introduce errors and reduce the reliability of conclusions. Additionally, LCA's focus primarily on environmental aspects may overlook crucial economic and social dimensions, limiting a comprehensive understanding of sustainability. Furthermore, LCA's applicability may be confined to specific areas such as waste management and policy formulation, potentially highlighting potential rather than actual impacts throughout the life cycle. In conclusion, while LCA remains a powerful sustainability assessment tool, addressing its limitations in scope definition, data quality, and holistic analysis is crucial. Improved transparency, standardized guidelines, and enhanced education and training can help mitigate these challenges, thereby enhancing the value of LCA in sustainable decision-making processes.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter investigates the methodology used in a thorough study that employs the life cycle assessment (LCA) framework to analyze sludge management. Following the guidelines set out in ISO 14040, the research involves four key stages: defining goals and scope, conducting a life cycle inventory, evaluating life cycle impacts, and interpreting the life cycle. The main goal of this research is to evaluate the environmental impacts associated with various sludge disposal methods and ultimately determine the most suitable approach for the final disposal of treated sludge.

3.2 Research Tools

GaBi software stands out as a comprehensive tool for conducting LCA, enabling the analysis of input-output flows and the identification of potential environmental emissions. Adhering to the standardized framework outlined in the ISO 14000 series, GaBi ensures consistency and reliability in LCA methodology. In this study, the GaBi student version software will be employed to perform an LCA of treated municipal sludge and its final disposal routes from WWTPs, evaluating their environmental impacts. The software operates by connecting to a database via the internet to extract input and output data from comprehensive databases. When a process is recognized, GaBi automatically generates input and output data. Otherwise, manual database setup is required. Given that sludge treatment processes may not be readily available, these processes must be developed manually, necessitating detailed input and output data. Once all processes are established, they are interconnected within the software to ensure a coherent process chain and delineate system boundaries. GaBi software facilitates the identification of potential environmental impacts, including Global Warming Potential (GWP), Acidification Potential (AP), Marine Eutrophication (MAETP), Abiotic Depletion Fossil (ADPf), among others. Figure 3.2.1 illustrates the process flowchart for constructing an LCA model in GaBi software.

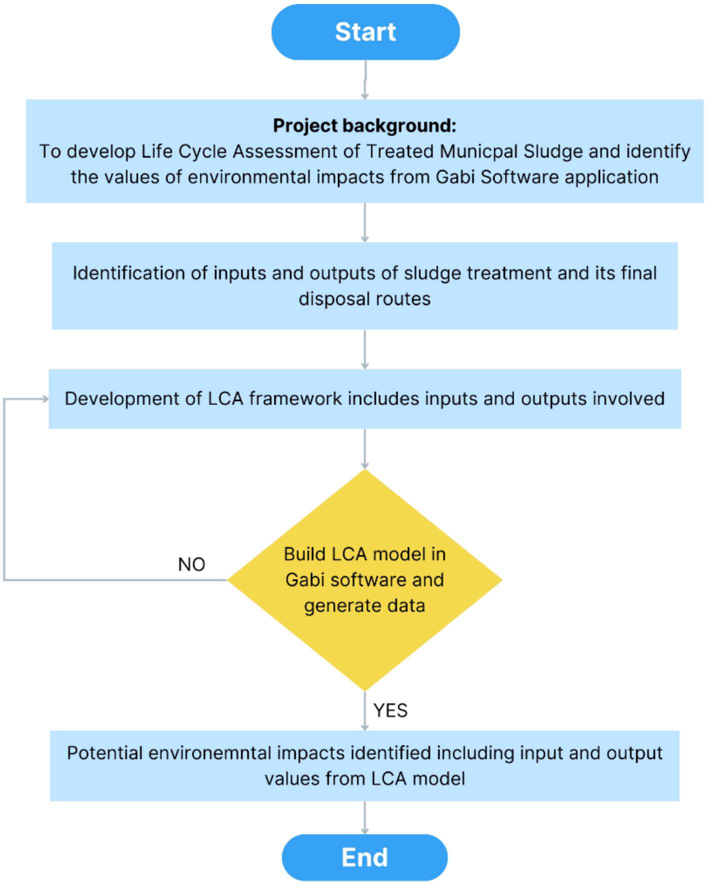


Figure 3.2.1 Process flowchart for LCA model using GaBi software

3.3 Research Area

The findings from this study aim to provide valuable insights to formulate sustainable and environmentally friendly strategies for sludge disposal, minimize the negative environmental impacts of sludge management, and increase awareness of the environmental implications of WWTP processes. The product under examination in this LCA study is the treated sludge generated during wastewater treatment operations The environmental effects of various sludge management methods in Malaysia will be studied at a wastewater treatment facility in Kuala Lumpur. A visit to the site was undertaken in order to comprehend the processes of the WWTP and determine all the inputs and outputs that will be evaluated in the research. Table 3.3.1 displays the overall details of the treatment plant while figure 3.3.1 illustrates the treatment plant process in an overview.

Table 3.3.1: General information of wastewater treatment plant located in KL.

Wastewater Treatment plant information	Value	Unit
Site area	17	hectares
Catchment area	6,700	hectares
Population equivalent	1,423,000	PE
Source of influent	domestic sewage from residential area	
Influent discharge location	Klang river	
Sludge daily production	60-70	ton/day
Sewage flow rate	222,519	m^3/day
Equipment lifetime	20	years
Plant removal efficiency	96	%
Influent characteristics		
COD	500	mg/L

BOD	250	mg/L
Oil & grease	50	mg/L
Total Phosphorus	17	mg/L
TSS	300	mg/L
TKN	50	mg/L
Effluent characteristics		
COD	200	mg/L
BOD	50	mg/L
Oil & grease	10	mg/L
Total Phosphorus	10	mg/L
TSS	100	mg/L
TKN	NA	mg/L
Dry sludge cake characteristics		
pH	6.2	-
Organic content	6.8	%
TKN	10,800	mg/kg
Moisture factor	23	%
Salmonella	absent	in 100mL
E coli	1.2×10^4	CFU/100mL
VS/TS ratio	14.63	%
Total metals		
Mercury	< 0.50	mg/kg
Arsenic	78	mg/kg
Chromium	57	mg/kg
Copper	110	mg/kg
Cadmium	< 5	mg/kg
Zinc	1,000	mg/kg
Lead	25	mg/kg
Total Nickel	16	mg/kg
Phosphorus	18,000	mg/kg

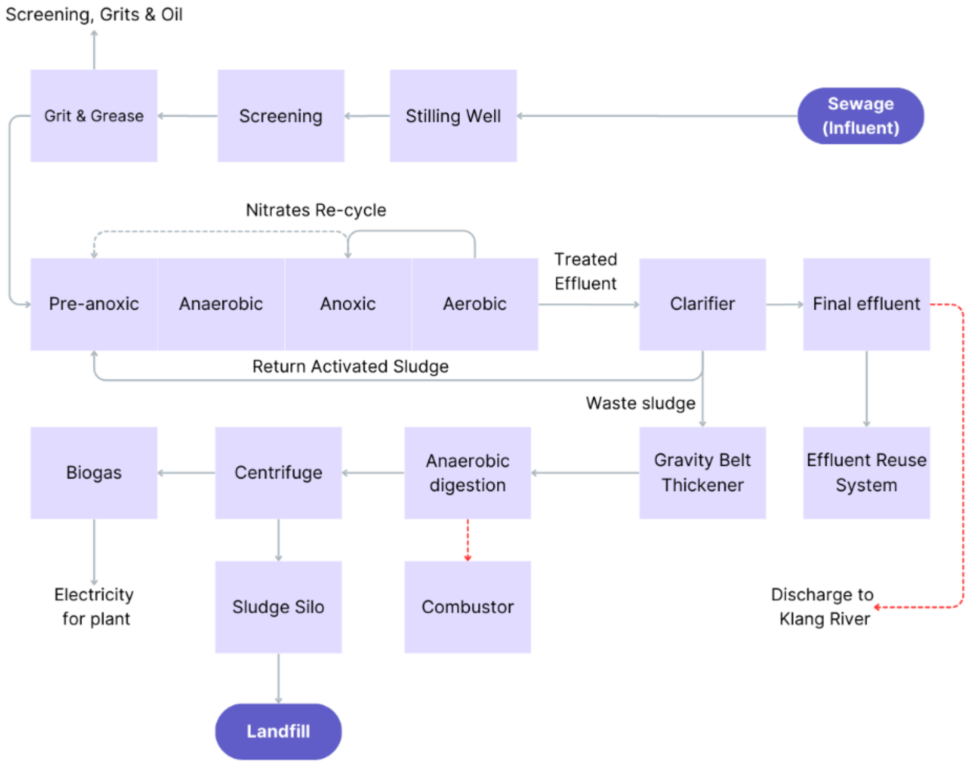


Figure 3.3.1: Overview of wastewater treatment plant process

As observed from Figure 3.3.1, the WWTP in Kuala Lumpur focuses on treating effluent generated by households, accommodating approximately 1,423,000 population equivalents (PE), primarily utilizing anaerobic digestion technology to treat the municipal sludge before it is sent to the landfill for final disposal.

3.4 Raw data

This study will concentrate on assessing three different methods for managing sludge: disposal in landfills, burning it in incinerators, and spreading it on land. The main goal is to find the most eco-friendly and sustainable waste disposal method, taking into account the problem of limited landfill space in Malaysia. Some assumptions were made about the system boundary due to limitations in input and output data availability. More specifically, it is assumed that the distance for transporting waste to the incinerator is 60km, whereas the distance for land application is 20km. The scope of the LCA analysis does not encompass the building of treatment plants, machinery, and auxiliary equipment, as their environmental effects are considered negligible in comparison to the ongoing operation (Roldán et al., 2020). Rather than that, the research will focus on a portion of the life cycle of a WWTP, specifically from the sludge production to the disposal routes, as shown in Figure 3.4.1 provided.

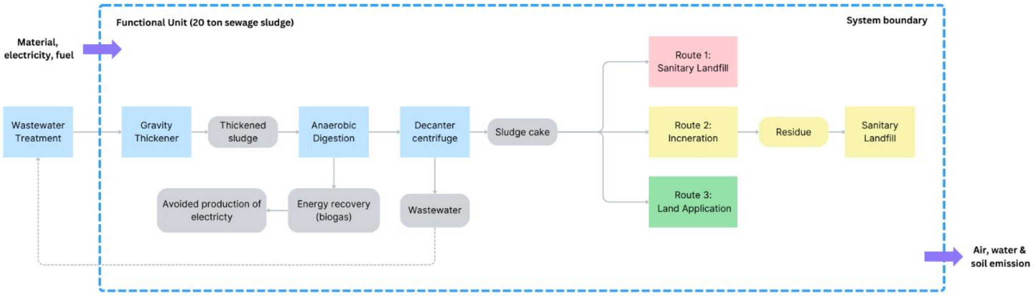


Figure 3.4.1: System boundary of the LCA study

3.5 Life Cycle Inventory Data

The life cycle inventory (LCI) involves quantifying the inputs and outputs of data associated with the system. Data is sourced from three different sources: (i) information gathered during site studies encompassing treatment processes, chemical usage, energy consumption, transportation, and direct emissions, (ii) relevant scientific literature for direct emissions, and (iii) the GaBi database for transportation, electricity mix, landfill, land application, and incineration. The inventory data for different sludge disposal methods are outlined in Table 3.5.1 (for landfilling), Table 3.5.2 (for incineration), and Table 3.5.3 (for land application), which was obtained from site visits and literature sources. Additionally, Table 3.5.4 displays the external processes provided in the GaBi database, which are utilized in this LCA study to evaluate the environmental impacts of sludge.

Table 3.5.1: Inventory data for route 1 (landfill)

Process	Type	Flow	Amount	Unit	Data source
Gravity Thickener	In	Sewage Sludge	20	t	site visit
	In	Polymer	13.42	kg	site visit
	Out	Gravity thickened sludge (97% moisture content)	18.11	t	site visit
Anaerobic digestion	In	Gravity thickened sludge (97% moisture content)	18.11	t	site visit
	In	Electricity	58.62	kWh	site visit
	Out	Emission to air, biogenic CO_2	11.43	kg	site visit
	Out	Emission to air, CH_4	5.04	kg	site visit
	Out	Emission to air, NO_x	1.03	kg	Li et al., 2017, Nielsen et al., 2010
	Out	Emission to air, N_2O	7.86	g	Li et al., 2017, Nielsen et al., 2010
	Out	Heat produced	4,848,593.27	kJ	site visit
	Out	Anaerobically digested sludge	15.66	t	site visit
	Out	Produced electricity	303.68	kWh	site visit
Decanter centrifuge	In	Anaerobically digested sludge	15.66	t	site visit
	In	Electricity	90.35	kWh	site visit
	Out	Digested sludge (23% moisture content)	13.17	t	site visit
	Out	Wastewater	138.1	m3	site visit
Transportation to disposal site	-	-	60	km	site visit
Sanitary landfill	In	Sludge cake	13.17	t	site visit
	Out	Landfill	-	-	[EU-28] Municipal solid waste on landfill including landfill gas utilization and leachate treatment, without collection, transport and pre-treatment

Table 3.5.2: Inventory data for route 2 (incinerator)

Process	Type	Flow	Amount	Unit	Data source
Gravity Thickener	In	Sewage Sludge	20	t	site visit
	In	Polymer	13.42	kg	site visit
	Out	Gravity thickened sludge (97% moisture content)	18.11	t	site visit
Anaerobic digestion	In	Gravity thickened sludge (97% moisture content)	18.11	t	site visit
	In	Electricity	58.62	kWh	site visit
	Out	Emission to air, biogenic CO_2	11.43	kg	site visit
	Out	Emission to air, CH_4	5.04	kg	site visit
	Out	Emission to air, NO_x	1.03	kg	Li et al., 2017, Nielsen et al., 2010
	Out	Emission to air, N_2O	7.86	g	Li et al., 2017, Nielsen et al., 2010
	Out	Heat produced	4,848,593.27	kJ	site visit
	Out	Anaerobically digested sludge	15.66	t	site visit
	Out	Produced electricity	303.68	kWh	site visit
Decanter centrifuge	In	Anaerobically digested sludge	15.66	t	site visit
	In	Electricity	90.35	kWh	site visit
	Out	Digested sludge (23% moisture content)	13.17	t	site visit
	Out	Wastewater	138.1	m3	site visit
Transportation to disposal site	-	-	60	km	assumption
Incinerator	In	Sludge cake	13.17	t	site visit
	-	Waste incineration plant	-	-	[DE] waste-to-energy plant with dry flue gas treatment, without collection, transport and pre-treatment
Landfill	-	Sanitary Landfill	-	-	[EU-28] Municipal solid waste on landfill including landfill gas utilization and leachate treatment, without collection, transport and pre-treatment

Table 3.5.3: Inventory data for route 3 (land application)

Process	Type	Flow	Amount	Unit	Data source
Gravity Thickener	In	Sewage Sludge	20	t	site visit
	In	Polymer	13.42	kg	site visit
	Out	Gravity thickened sludge (97% moisture content)	18.11	t	site visit
Anaerobic digestion	In	Gravity thickened sludge (97% moisture content)	18.11	t	site visit
	In	Electricity	58.62	kWh	site visit
	Out	Emission to air, biogenic CO_2	11.43	kg	site visit
	Out	Emission to air, CH_4	5.04	kg	site visit
	Out	Emission to air, NO_x	1.03	kg	Li et al., 2017, Nielsen et al., 2010
	Out	Emission to air, N_2O	7.86	g	Li et al., 2017, Nielsen et al., 2010
	Out	Heat produced	4,848,593.27	kJ	site visit
	Out	Anaerobically digested sludge	15.66	t	site visit
	Out	Produced electricity	303.68	kWh	site visit
Decanter centrifuge	In	Anaerobically digested sludge	15.66	t	site visit
	In	Electricity	90.35	kWh	site visit
	Out	Digested sludge (23% moisture content)	13.17	t	site visit
	Out	Wastewater	138.1	m3	site visit
Transportation to disposal site	-	-	20	km	assumption
Land application	In	Sludge cake	13.17	t	site visit
	Out	land application	-	-	[DE] technology mix, production mix at plant. sludge application on land

Table 3.5.4: Choice of background information

External process	Data source (GaBi database)
Electricity grid mix	[MY] AC, technology mix, consumption mix, to consumer
Diesel mix at refinery	[CN] from crude oil and bio components, production rate, at refinery, 800ppm sulphur, 0.10 wt.% bio components
Transportation	[GLO] Truck, Euro 4, 34 - 40t gross weight/27t payload capacity
Avoided electricity (biogas)	[DE] mix of direct and CHP, technology mix regarding firing and flue gas cleaning, production mix at power plant (1kV – 60kV)

3.6 Life Cycle Impact Assessment

In LCIA, the environmental impacts found in the inventory analysis are carefully reviewed and assessed. This procedure includes converting input information into environmental effects throughout the product's entire life cycle, usually determined by a specific functional unit. LCIA involves four main stages: choosing and specifying impact categories, categorization, characterization, and normalization. The impact assessment method chosen for the study is the CML2001 method. This decision is essential for meeting the goals of the study, since each LCIA method addresses various impact categories and characterization factors. In the classification process, the raw data from the life cycle inventory (LCI) is distributed among the chosen impact categories. Afterwards, characterization is used to determine the outcomes of impact indicators using the given data. In the normalization phase, the impact indicator results are modified to match related data, allowing for a thorough evaluation.

3.7 Life Cycle Interpretation

The final stage of the life cycle assessment process is life cycle interpretation (LCI), a crucial step in making informed judgments and recommendations. In this study, the outcomes of various sludge management methods are interpreted to mitigate the environmental burden associated with sludge disposal in the wastewater sector. By carefully considering the results of impact categories, stakeholders in the wastewater sector can explore alternative sludge management approaches that exhibit lower environmental impacts across the entire life cycle. Drawing insights from a study by Yu et al. (2023), it is anticipated that sanitary landfilling will contribute the highest carbon emissions due to methane gas generation during organic waste decomposition. Conversely, incineration is projected to yield relatively lower carbon emissions compared to other disposal methods, attributed to the utilization of mechanical drying techniques that reduce sludge cake moisture content, subsequently lowering energy requirements and fossil fuel usage during the incineration process. Land application is expected to result in the lowest carbon emissions. This is because the application of sewage sludge in agricultural settings can substitute the need for chemical fertilizers, thereby enhancing soil structure and improving workability for agricultural practices. These insights underscore the importance of considering environmental impacts when making decisions regarding sludge management strategies within the wastewater sector. (Aggelides and Londra, 2000; Singh and Agrawal, 2008; Torri and Lavado, 2008; Wang et al., 2008; Haynes, Murtaza and Naidu, 2009)

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter discusses the results of the LCIA carried out on three various sludge handling techniques for 20 tons of sewage sludge, which is the functional unit of the LCA research, using the CML2001 approach. The CML2001 approach provides a predetermined group of indicator scores that reflect the seriousness of different environmental impact categories. This research examines only five midpoint indicators out of the total twelve, emphasizing the most important impacts for analysis: global warming potential (GWP), abiotic depletion fossil (ADPf), acidification potential (EP), human toxicity potential (HTP), and marine aquatic ecotoxicity potential (MAETP). By utilizing LCIA, the activities with the most significant direct impacts on the environment will be pinpointed. Afterwards, the collected information will be analyzed and converted into bar graphs. The best way to dispose of sludge sustainably can be found by analyzing the environmental effects through GaBi software.

4.2 Global Warming Potential

Phang (2024) states that Malaysia has pledged to the Paris Agreement, with a goal of decreasing GDP intensity emissions by 45% by 2030 and striving to reach carbon neutrality by 2050. This project has sparked curiosity among different industries. An examination of the carbon footprint linked to three methods of managing sludge shows notable environmental effects, especially in relation to global warming potential (GWP). GWP quantifies emissions in kilograms of CO_2 equivalents and takes into account carbon dioxide, methane, and carbon monoxide. Teppfa (n.d.) describes GWP as the quantity of carbon dioxide (CO_2) needed to produce a similar atmospheric heat-trapping impact as different greenhouse gases during a standard 100-year period (GWP100). The GWP indicators of three sludge disposal techniques - landfilling, incineration, and land application - are examined and converted into flow charts. Figures 4.2.1 depict the carbon emissions during each phase of various sludge management processes, starting from production until the end of its life cycle.

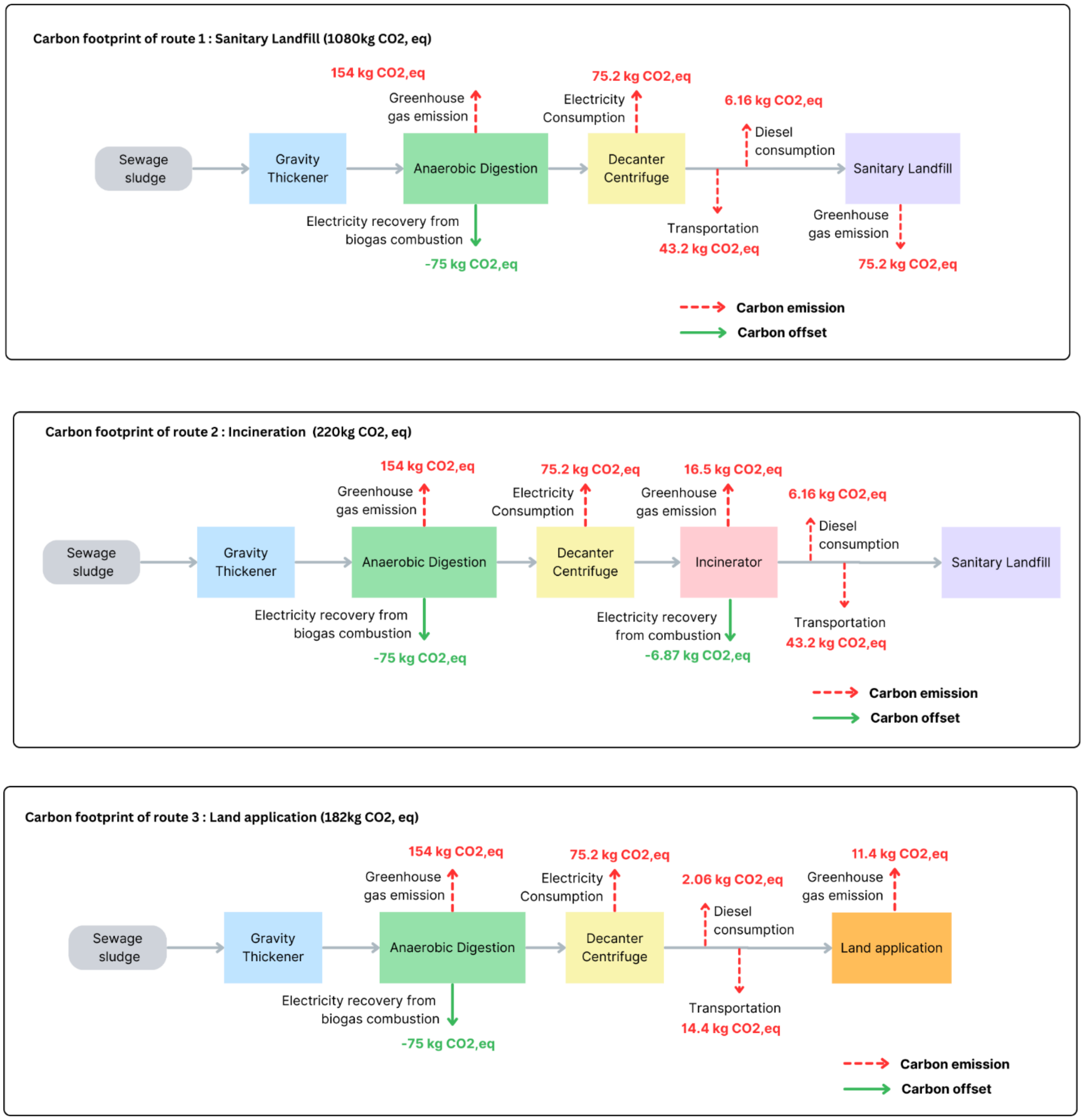


Figure 4.2.1: Carbon footprint of different routes (sanitary landfill, incineration and land application)

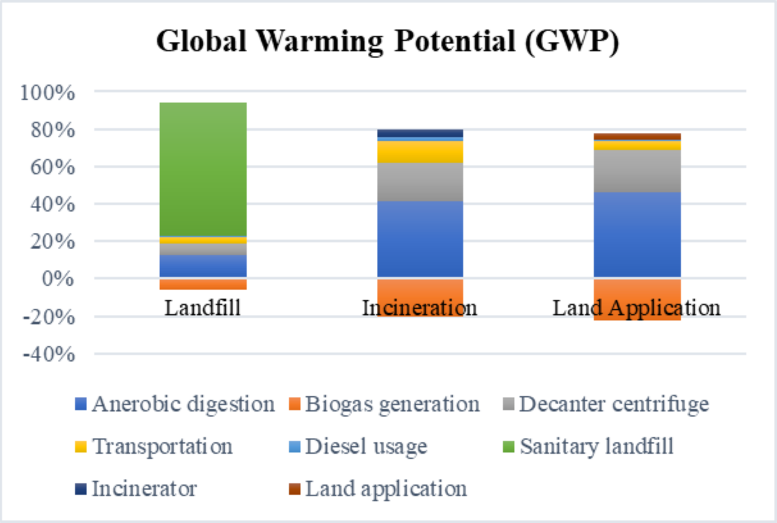


Figure 4.2.2: Global warming potential

As illustrated in figure 4.2.1, landfilling produces the highest GWP (1080.56 kg CO_2 eq), followed by incineration (220.09 kg CO_2 eq) and land application (182.06 kg CO_2 eq). The significant GWP associated with landfilling is primarily due to the anaerobic decomposition of waste, resulting in methane gas emissions. In the CML2001 method, the emission of 1 kg of methane is equivalent to 28 kg CO_2 equivalents, significantly contributing to the overall carbon footprint of landfills. The degradation of waste in landfills generates approximately 24% carbon dioxide and 76% methane gas, contributing to the high GWP value. On the other hand, incineration, the second-lowest carbon emitter, involves combusting waste with fuel to produce steam for electric generator turbines. Although incineration emits CO_2 and N_2O into the atmosphere, energy recovery mitigates environmental impacts by converting waste into energy. Furthermore, incineration poses a lower risk of soil and water pollution than landfilling, making it a globally favoured method for waste volume reduction before landfill disposal (Malet et al., 2023).

Furthermore, using anaerobic digestion systems helps in capturing biogas, which usually contains 60-70% methane, 30-40% carbon dioxide, and small quantities of other gases like hydrogen sulfide, ammonia, hydrogen, nitrogen gas, and carbon monoxide. This biogas can be used for renewable energy purposes or burned to avoid its emission as a powerful greenhouse gas (GHG) (Bracmort, 2010). The biogas that has been collected can be used as a fuel to create heat or produce electricity, with any extra electricity being used for activities at the AD facility. Although there are carbon emissions involved in transporting digestates to disposal sites, the advantages of replacing fossil fuels and storing carbon in the soil are greater than these drawbacks. Hence, these emissions are classified as avoided emissions, since they indicate the emissions that would have taken place if a comparable quantity of non-renewable energy had been employed. Utilization of AD technology assists in lessening the overall environmental impact of the WWTP. The study takes into account the GWP impacts of transporting digestates to the final disposal site, including factors such as the transportation vehicle and the distance to the spreading site, landfill, and incinerator. The study utilized a truck as the transportation vehicle, which had an emission factor of 5.46 grams of CO_2 equivalent per tonne per kilometer. The digestate is believed to be carried 20 km to the land application site (producing 14.4 kg CO_2 eq), 60 km to the sanitary landfill site (resulting in 43.2 kg CO_2 eq), and to the incinerator (also resulting in 43.2 kg CO_2 eq) from the anaerobic digestion plant. However, the anaerobic digestion process had minimal avoided emissions as the plant had restrictions in heat recovery capabilities (Malet et al., 2023).

On the other hand, the utilization of sewage sludge through land application demonstrates the lowest Global Warming Potential (GWP) impacts and is widely acknowledged as the most economically efficient approach for sludge disposal. This method effectively replaces the requirement for chemical fertilizers and pesticides, thus establishing its environmental superiority (Champagne, 2007; Singh and Agrawal, 2008; Haynes, Murtaza and Naidu, 2009; Lu, He and Stoffella, 2012). The land application practice involves the spreading of sludge either on the soil surface or slightly below it, at a depth ranging from 15 to 30 cm (Epstein, 2002; Del Mar et al., 2006; Wang et al., 2008). Furthermore, the utilization of sewage sludge through land application has been a longstanding practice in numerous countries for centuries (Singh and Agrawal, 2008).

Sewage sludge primarily consists of partially decomposed organic matter (30.0–60.0%) and essential plant nutrients such as nitrogen (N) (0.5–10.0%), phosphorus (P) (1.0–6.0%), sulfur (0.5–1.5%), calcium (1.0–20.0%), magnesium (0.3–2.0%), as well as micronutrients like iron (0.1–5.0%), copper, manganese, zinc (<0.2%), nickel, boron, cobalt, and molybdenum (<0.05%) (Basta,1995). Through the addition of sewage sludge, the soil's organic carbon content, electrical conductance, cation exchange capacity, as well as nitrogen and phosphorus levels are enhanced (Singh and Agrawal, 2008). Consequently, the land application of sewage sludge has the potential to augment soil carbon storage and accrue credits for carbon sequestration (Sylvis, 2009).

Compared to a prior study by Zhou et al. (2022), the distribution of carbon emissions among three different sludge management methods—land application, incineration, and landfill—is notably different. While the previous study reported a ratio of 1:3:12 respectively, this study yielded a ratio of 2:3:12. Interestingly, the emissions from land application in this study were slightly higher than those reported by Zhou et al. (2022). This variance can be attributed to differences in the input and output processes and emissions associated with land application. The discrepancy likely arises from the methodologies employed and the specific contexts of each study. This study relied on data from the GaBi database, which utilizes the land application process prevalent in Germany. In contrast, Zhou et al. (2022) based their findings on emissions observed from actual land application practices within wastewater treatment plants in China. This disparity in geographic context is crucial, as environmental regulations, waste management practices, and even climatic conditions can vary significantly between countries (Li et al., 2022). The differences in sludge characteristics, treatment methods, and transportation logistics may also contribute to variations in emission levels. Therefore, the contrasting results between this study and that of Zhou et al. (2022) underscore the importance of considering regional factors and local practices when assessing environmental impacts. This highlights the need for context-specific approaches in evaluating the environmental impacts of sludge management practices, particularly concerning global warming potential.

4.3 Abiotic Depletion (ADP Fossil)

Abiotic Depletion (fossil), or ADPf, refers to the excessive extraction of fossil fuels, encompassing resources like coal, natural gas, and diesel. This depletion is calculated based on the calorific value of the depleted fuel and reflects the impact of diesel consumption throughout various lifecycle stages (teppfa, n.d.). The primary source of ADPf originates from the over-extraction and consumption of fossil fuel resources beyond natural replenishment rates, leading to gradual depletion and increased GHG emissions (Van Oers et al., 2016).

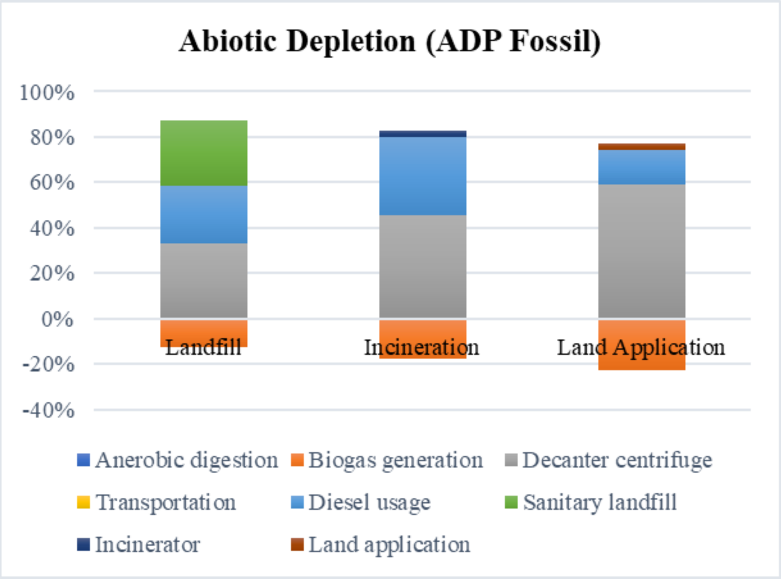


Figure 4.3.1: Abiotic Depletion (ADP Fossil)

Based on the results shown in Figure 4.3.1 for the ADPf impact indicators, a significant portion of the high ADPf value of treated sludge arises from the treatment process, notably using decanter centrifuges and transporting sludge to disposal sites. Transportation accounts for approximately 27-33% of the total ADPf impacts, primarily due to truck diesel usage. The decanter centrifuge plays a crucial role in separating solids from wastewater, operating on the principle of centrifugal force generated by electricity. This process effectively handles large volumes of sludge separation and is widely employed in WWTPs globally. The purpose of the decanter centrifuge is to reduce the moisture content of digested sludge, facilitating its transportation, disposal, and beneficial utilization. Decreasing moisture content reduces sludge's mass and volume, making it more manageable and cost-effective for transportation, landfilling (thus improving landfill stability by reducing leachate generation), incineration, or land application for soil enhancement. Ensuring proper moisture levels, as advised by Judd (2020), is essential for efficient incineration, minimizing the formation of secondary hazardous pollutants like dioxins, furans, NOx (oxides of nitrogen), and SO_2 (sulphur dioxide). The figure above shows that the electricity consumption of the decanter centrifuge amounts to 90.35 kWh, resulting in an ADPf equivalent of 885MJ, which is used to reduce the moisture content of 13.17t of digested sludge. Furthermore, electricity production from anaerobic digestion (AD) biogas is a fossil fuel replacement, generating credits equivalent to -341MJ of ADP fossil. The credit for electricity production varies based on plant operation. In Malaysia's 2020 electricity mix (obtained from the GaBi database), each kWh produced resulted in 0.832 kg CO_2 eq, with 75 kg CO_2 eq used for electricity production credit, as illustrated in figure 4.1.2 Global Warming Potential.

Among the three disposal routes, landfilling has the greatest impact on ADPf, with the landfill itself responsible for 39% of total ADPf impacts. ADPf is closely tied to natural resource consumption, and its effects increase as the amount of sludge or waste deposited in landfills grows. Recycling sludge for land application reduces the need for chemical fertilizers and pesticides, leading to improved crop yield and soil structure, which in turn facilitates ploughing and tilling activities (Aggelides and Londra, 2000; Singh and Agrawal, 2008; Torri and Lavado, 2008; Wang et al., 2008; Haynes, Murtaza and Naidu, 2009). This results in reduced energy consumption and greenhouse gas (GHG) emissions from chemical fertilizer and pesticide production. Furthermore, the fossil fuel required for tractor operations during irrigation is decreased, along with associated GHG emissions. Application of sewage sludge enhances soil properties such as aggregate stability, water retention capacity, porosity, and humus content. It also reduces soil bulk density and erosion. On the other hand, incineration of sewage sludge involves energy recovery through burning, which replaces traditional electricity production and helps mitigate environmental impacts linked to fossil fuel use. Since energy recovery in landfill systems is lower compared to incinerators, fossil resource depletion (with credits) is significantly higher in landfills. While incineration may have greater impacts on human health due to dioxin and furan emissions, it is still a more sustainable option than landfilling, especially for countries with limited land space for constructing landfills.

4.4 Acidification Potential

Acidification Potential (AP) indicates the environmental impact of emissions like sulfur dioxide (SO_2) and nitrogen oxides (NO_x) released during industrial activities. These releases may result in the creation of acid rain, which has adverse effects on soil, water sources, human health, and ecosystems. The quantification of AP is determined by the quantity of sulfur dioxide required to cause the same level of acidification as the acidic gases interacting with water in the atmosphere, measured in kilograms of SO2 equivalent (teppfa, n.d.). The main factor that affects environmental acidity is the acidification potential, which plays a role in damaging infrastructure, water sources, and biodiversity. It includes processes that increase the levels of acidity in water and soil, which can be harmful to plants and animals. Key substances contributing to acidification potential include NO_x, SO_x, NH_3, and HCl, which, upon deposition, can harm animal and plant populations (Dincer and Bicer, 2018).

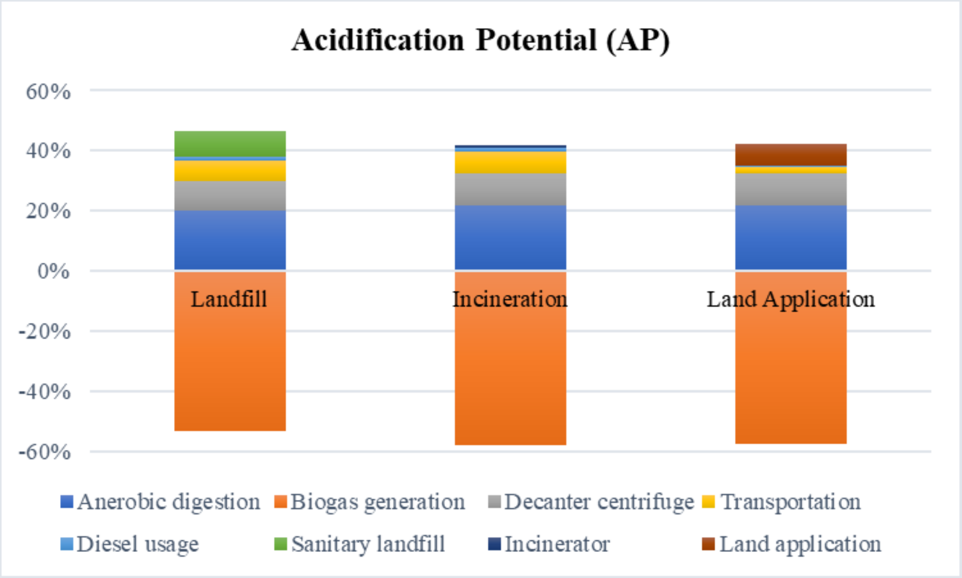


Figure 4.4.1: Acidification Potential (AP)

The acidification impact indicator results from LCIA, shown in figure 4.4.1, illustrate the notable impacts of certain factors during various phases of the sludge management process. Ammonia is the main element in pre-processing, solid composting, and biogas slurry composting stages. On the other hand, nitrogen oxides are the main pollutants in the collection and transportation stages, as well as in biogas power generation and heating phases. Sulfur oxides, mainly generated from anaerobic digestion, also contribute significantly to acidification, highlighting the important roles of ammonia and nitrogen oxides in this phenomenon. AP's main impact comes from sludge disposal in landfills and on land, which could lead to higher levels of heavy metal contamination. Landfilling has a greater acidification potential than land application, with 0.916 kg SO_2 eq and 0.221 kg SO_2 eq, respectively. Air pollutants like hydrogen sulfide, ammonia nitrogen, NO_x, and SO_x are responsible for causing acidification, with ammonia nitrogen from leachate making up 98.5% of the acidification potential in landfills according to Haynes, Murtaza, and Naidu (2009). Gasification also plays a major role in air pollution mostly due to NOx emissions. Emissions of ammonia-containing substances from sludge used as fertilizers in land application are the main cause of acidification during the spreading of sludge on land.

4.5 Human Toxicity Potential

Human Toxicity Potential (HTP) is a calculated index that shows how much harm a specific amount of chemical released into the environment can cause to human health, particularly from toxic substances. It takes into account the compound's inherent toxicity and potential dose, without considering risks from workplace exposure (EG Hertwich et al., 2001). The Uniform System for the Evaluation of Substances adapted for Life Cycle Assessment (USES-LCA) is used to determine characterization factors for HTP in terms of 1,4-dichlorobenzene equivalents per kilogram of emission. This provides information on the destiny, exposure, and impacts of toxic substances over an unlimited time horizon (Yang et al., 2023). Sewage sludge commonly holds harmful inorganic substances like metals (e.g., zinc, nickel, mercury, chromium) and non-metals (e.g., arsenic), often traced back to industrial waste and deteriorated sewage systems. The primary factors influencing the HTP category come from generating electricity using fossil fuels such as arsenic, hydrogen fluoride, and sodium dichromate (Aitor P. Acero, Cristina Rodríguez, and Andreas Ciroth, 2016).

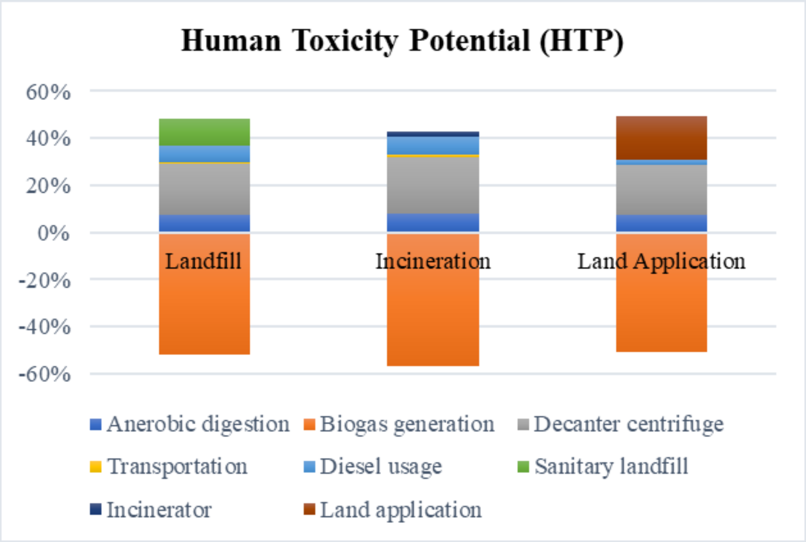


Figure 4.5.1: Human Toxicity Potential (HTP)

Figure 4.5.1 shows the evaluation of HTP in relation to different sludge disposal techniques. The study shows that applying sewage sludge to farmland is the most harmful process, accounting for around 90% of the impact caused by heavy metals. Polycyclic aromatic hydrocarbons (PAHs) and lead are particularly highlighted as the most harmful substances in this situation (Pozzebon and Seifert, 2023). However, land applying sewage sludge has the highest HTP compared to burning and burying, mainly because heavy metals and other contaminants can be released and exposed during this process. Despite the health risks associated with sludge incineration, such as the release of harmful pollutants like sulfur dioxide, nitrogen oxides, and dioxins, it is crucial to effectively control these substances to reduce negative health impacts. Moreover, sewage sludge is able to absorb emerging contaminants like pharmaceuticals and personal care items, which could have long-lasting effects on human health if not properly controlled (Yakamercan, Ari, and Aygün, 2021). Hence, the wastewater treatment sector must conduct a thorough assessment of the environmental effects of organic waste disposal methods in response to growing environmental apprehensions. It is crucial to conduct a comprehensive examination of sludge composition to verify that heavy metal and contaminant concentrations adhere to safe thresholds prior to its use on land. This is necessary in order to avoid crop contamination and potential detrimental health impacts on individuals from consuming contaminated produce.

Moreover, biosolids consist of trace metal elements, trace compounds, and pathogens that have the potential to be transferred to plants, livestock, and humans. Even though biosolids offer advantages for improving soil quality with their rich levels of nitrogen, phosphorus, organic carbon, and other crucial nutrients, they also act as repositories for new pollutants. Reducing negative exposures to these new pollutants when applied to land remains difficult, requiring a thorough review of waste disposal practices in the wastewater treatment industry. In Malaysia, regulations have been put in place to set technical standards for the utilization of biosolids in both agricultural and non-agricultural settings. These regulations are aimed at ensuring that nutrient levels, pathogenic microbes, and pollutants remain within acceptable limits, as well as overseeing biosolid management, storage, and monitoring. It is required to get a certificate of analysis from a recognized lab before applying biosolids on land to ensure adherence to allowable limits and correct management methods, increasing plant nutrient absorption and decreasing the chances of being exposed to pathogens, heavy metals, and other pollutants in sewage sludge (SPAN, 2020a; 2020b). Recognizing sustainable methods for managing biosolids is essential for enhancing efficiency in resource utilization, conserving resources, and minimizing emissions of pollutants. These practices help promote sustainable management by improving the efficiency of resource utilization, preserving resources, and reducing pollutant emissions.

4.6 Marine Aquatic Ecotoxicity Potential

MAETP is a measure of environmental impact, assessing heavy metal concentration in water and reported in kilograms of DCB equivalents (Zhang et al., 2019b). These heavy metals typically come from activities like generating electricity at landfills and treating wastewater. Cadmium, mercury, arsenic, and lead are important contributors to MAETP, especially cadmium and mercury which are highly prevalent in the landfill wastewater treatment process (Zhang et al., 2019b). The MAETP is especially affected by water, since treating wastewater can result in the release of dangerous heavy metals and inorganic substances into fresh water, air, and soil, thus affecting the aquatic environment directly and indirectly.

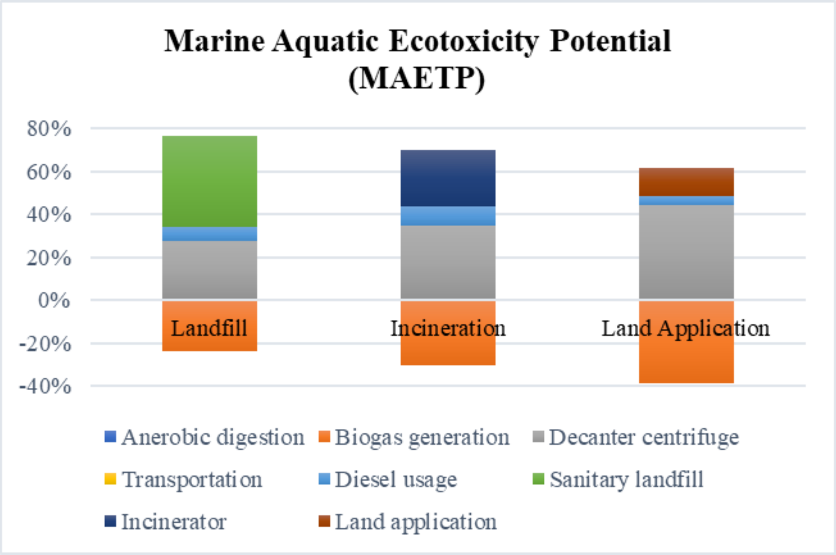


Figure 4.6.1: Marine Aquatic Ecotoxicity Potential (MAETP)

Figure 4.6.1 illustrates a significant difference in the MAETP between dumping in landfills and burning in incinerators. Landfill leachate is the main source (82%) of MAETP, causing an estimated equivalent of 5160 kg DCB for landfilling versus 2500 kg DCB for incineration (Atılgan Türkmen, 2022). In spite of being commonly utilized, incineration poses significant threats to the toxicity of marine ecosystems. Pollutants from incineration, such as mercury, lead, cadmium, dioxins, and furans, can be deposited into water bodies through the air, leading to contamination of marine ecosystems (Atılgan Türkmen, 2022). Moreover, the leftover ash from burning contains high levels of pollutants that may not be fully eliminated during incineration. The environmental impact of incineration is largely due to the introduction of metals like nickel, beryllium, cobalt, vanadium, and copper into freshwater, making up a substantial portion (97.9%) of the impact (Atılgan Türkmen, 2022).

In addition, the discharge of ash produced in incinerators into landfills may lead to the release of contaminants into adjacent water sources, adding to the pollution of aquatic environments (Jeswani and Azapagic, 2016). Some pollutants emitted during incineration can build up in marine organisms, causing them to accumulate in tissues as they move up the food chain, a process known as biomagnification. Additionally, when ash from incineration comes into contact with water, such as during rainfall, it can create leachate that may carry harmful chemicals and harm aquatic habitats by seeping into groundwater and surface water.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This study extensively evaluated the environmental impacts of treated municipal sludge using Life Cycle Assessment (LCA). Its objectives were successfully achieved, including the identification of the life cycle inventory of sludge treatment WWTPs and the determination of environmental impacts of various sludge disposal routes in a gate-to-grave manner, employing the CML2001 method. This approach highlights intermediate impact assessment categories, placing importance on the initial stages of cause and effect to reduce uncertainties related to quantitative modelling.

Findings produced using the CML2001 approach included measurements for global warming potential (GWP), abiotic depletion fossil (ADPf), acidification potential (AP), human toxicity potential (HTP), and marine aquatic toxicity potential (MAETP). Visual representations showed the differing contributions of each disposal method to these specific categories. Landfilling was found to be the least sustainable choice, with greenhouse gas and acidifying emissions mainly caused by methane release from landfill decomposition and contamination of leachate. The main causes are methane being released from decomposing landfills and leachate pollution from H_2S, NH_3-N, NO_x, and SO_x. However, incineration is efficient in reducing waste volume and is considered a sustainable method for recovering energy, resulting in reductions in greenhouse gas emissions and depletion of abiotic resources due to the decreased use of fossil fuels in the waste combustion process. Nonetheless, incineration continues to present dangers of air and water contamination, primarily caused by byproducts such as dioxin and furan in air emissions, as well as ash containing heavy metals that can affect water and nearby surroundings, leading to HTP and MAETP. The use of sewage sludge on land showed the least amount of global warming potential, abiotic depletion potential fossil fuels, and acidification potential, as it replaces the production of chemical fertilizers and avoids negative impacts. Nevertheless, worries about heavy metal pollution require stringent regulations to guarantee the safety of the environment and human health. Nevertheless, worries about the presence of heavy metal pollution in sewage sludge can lead to high toxicity potential. Hence, it is necessary for sludge producers to adhere to strict regulations in order to ensure that heavy metals and pathogens in sewage sludge do not exceed permissible limits before it is spread on land, in order to protect both environmental receptors and human health.

Another aspect worth mentioning in this research is the utilization of AD technology in WWTPs, leading to a decrease in general global warming potential and abiotic depletion of fossil fuels by producing biogas and surplus electricity. Reducing the dependence on non-renewable energy sources helps prevent the emission in question. Moreover, decanter centrifuges used in treatment facilities also have a significant impact on global warming because they require electricity to remove moisture from sludge before it is disposed of. Reducing the weight and size of the material is essential to lower shipping costs and optimize the incineration process for energy generation.

Malaysia's waste management heavily depends on depositing waste in landfills, which is expected to cause a shortage of landfills by 2050 because of the low rate of recycling and the large amount of waste produced daily by Malaysians. In the wastewater treatment plant sector, the growing volume of wastewater from residents has led to a rise in sludge production, with landfill disposal being the typical method for getting rid of it. While sludge disposal is not the primary cause of waste generation in Malaysia, it does add to the strain on inadequate landfill capacity. According to Azril's (2019) news report, IWK, Malaysia's biggest wastewater sector, collaborated with FRIM by signing an MoU to use treated water waste (biosolid) as fertilisers for non-edible plants, focusing on sludge disposal. Ongoing research and experimentation by pilot programs have investigated the use of biosolids as fertilizers for forest trees and rubber plantations, demonstrating promising outcomes in the rehabilitation of damaged lands. Current trials in the area are being conducted to evaluate the effectiveness and safety of powdered and pelletised fertiliser derived from treated sewage sludge for non-food plants, and results so far are encouraging. The government's assistance, such as offering incentives and enforcing regulations mandating the use of biofertilisers for certain purposes like landscaping and golf courses, is crucial for collaborating with operators to mitigate the environmental consequences and greenhouse gas emissions caused by sewage byproducts and decreasing dependence on imported chemical fertilisers. Hence, utilizing sludge for land application is a viable and effective option for the wastewater industry to decrease biosolid production and help reduce the environmental carbon footprint.

In summary, LCA is shown to be a successful approach for evaluating the environmental effects of sewage sludge management. By utilizing LCA, researchers can compare different methods of disposing sludge while taking into account factors like greenhouse gas emissions, energy use, water contamination, and human well-being in order to identify the most environmentally friendly disposal option. It acts as a guide for researchers to find a greener and more sustainable method for managing sewage sludge to complete the cycle.

5.2 Limitation of Study

The life cycle assessment in this study specifically looks at the gate-to-cradle analysis, covering the entire process from sludge production at WWTPs to the final disposal of the sludge. Limitations in obtaining inventory data from online sources and constraints related to the software's outdated version prevent the LCA study from including the stages of wastewater treatment and polymer production for sludge treatment. Recognizing that emissions and fuel consumption levels can vary, assumptions have been made for land application and incineration transportation distances of 20km and 60km, respectively. Due to the scarcity of incineration facilities in Malaysia, which are mainly used for treating hazardous and clinical waste, identifying a suitable location for incinerators in the research poses a difficulty. Moreover, despite ongoing testing for effectiveness in Malaysia, there is a lack of local data on the environmental effects of sewage sludge land application. As a result, a significant portion of the impact analysis is based on data obtained from Germany and China. Actual data from site visits and literature papers are used for the sludge treatment stage because the student version of GaBi software is outdated, with database records mainly from 2020. As a result, depending on outdated data could lead to less accurate and dependable outcomes in environmental impact assessments. Additionally, it is highlighted that the selection of a sustainable sludge disposal approach should consider more than just environmental consequences.

5.3 Recommendation and Improvements

Several recommendations can be proposed to address the study's limitations and enhance its reliability. Data sources for the WWTP industry, incineration, landfill, and land application processes remain limited in Malaysia. Therefore, further data collection on local disposal routes is necessary to enhance the study's credibility. One significant challenge in obtaining data from WWTP is the need for monitoring instruments across all process stages. Therefore, most data relies on information from literature papers and research articles. Additionally, transportation considerations are crucial, as they influence environmental impacts. Therefore, the study should prioritize specific roads and locations to improve accuracy. Moreover, more input data regarding polymer production in the GaBi student software must be collected, highlighting the need for additional studies to enhance reliability and accuracy. Besides, integrating Life Cycle Costing (LCC) into the study could offer a comprehensive overview of the feasibility of different disposal methods based on cost considerations. In GaBi software, cost information is categorized into flow, machine, and personnel costs, each encompassing various components; flow costs refer to the cost incurred during the production stage, including the cost of raw materials and manufacturing overhead ratio. On the other hand, machine costs refer to the cost of equipment or technology use, including cycle time (average time taken to process raw material into completed end product), direct cost per hour (operation cost of equipment for an hour) and overhead ratio. Personnel costs are the labour costs for employees, including cycle time, hourly wages and overhead ratio. A detailed data inventory required and formulae used in conducing LCC using GaBi software can refer to the GaBi Manual published by PE International AG (2012). In summary, conducting LCC for a WWTP requires essential inventories, including raw material costs for polymers, electricity expenses, transportation fuel costs, disposal costs for landfilling, incineration, and land application, machinery expenses for sludge treatment, labour costs, and overhead expenses.

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