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Semi-Aerobic Landfill System as Alternative Solution for Indonesian Landfill

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ABSTRAK

Indonesia telah menghadapi masalah mendesak dalam mengelola sampah kota (*Municipal Solid Waste*). Menurut data Kementerian Lingkungan Hidup dan Kehutanan (KLHK), hingga 35,46% TPA dikelola secara terbuka hingga Mei 2022 karena konsep sanitary landfill yang layak belum sepenuhnya diterapkan dan kondisi TPA di Indonesia yang mengalami kelebihan kapasitas. Dengan berkembangnya teknologi TPA, Kementerian Pekerjaan Umum saat ini mulai mengembangkan alternatif sistem TPA lainnya. Penelitian ini menggunakan pendekatan kualitatif dengan mengumpulkan data sekunder melalui penelitian kepustakaan dan tinjauan literatur, yang mencakup peraturan pemerintah dan penelitian sebelumnya. Analisis data dilakukan dengan menggunakan analisis SWOT, yang kemudian disusun ke dalam matriks SWOT untuk pemeriksaan komprehensif. Dari temuan umum penelitian ini, dapat disimpulkan bahwa sistem TPA semi-aerobik merupakan metode yang dapat digunakan sebagai solusi alternatif TPA Indonesia. Hal ini didasarkan pada hasil matriks SWOT, yang menunjukkan faktor-faktor strategis yang berasal dari faktor internal dan eksternal yang berasal dari penelitian sebelumnya dan isu-isu mengenai TPA di Indonesia. Analisis faktor-faktor tersebut menunjukkan bahwa sistem TPA semi-aerobik menghasilkan kinerja yang lebih baik dengan mengurangi potensi pencemaran lingkungan air dan udara serta emisi gas rumah kaca. Penerapan sistem TPA semi-aerobik adalah metode yang layak untuk digunakan di negara-negara berkembang.

***Kata kunci*:** semi-aerobik, TPA, analisis SWOT, alternatif, solusi, Indonesia

ABSTRACT

Indonesia has encountered pressing problems in managing municipal solid waste (MSW). According to data from the Ministry of Environment and Forestry (KLHK), up to 35.46% of landfills were run as open-dumping landfills until May 2022 because proper sanitary landfill concepts were not fully implemented and the condition of landfills in Indonesia is on the point of being overcapacity. With the development of landfill technology, the Ministry of Public Works is currently developing other alternative landfill systems. This research used a qualitative approach that gathered secondary data through library research and a literature review, encompassing government regulations and previous research. Analyzing the data entailed utilizing a SWOT analysis, which was then organized into a SWOT matrix for the comprehensive examination. From the general findings of this study, it can be concluded that the semi-aerobic landfill system is an available method to be used as an alternative solution for Indonesian landfills. This is based on the results of the SWOT matrix, which shows strategic factors derived from internal and external factors originating from previous studies and issues regarding landfills in Indonesia. The analysis of these factors shows that the semi-aerobic landfill system produces better performance by reducing the potential for environmental pollution of water and air and greenhouse gas emissions. The implementation of a semi-aerobic landfill system is a viable method to be used in developing countries.

***Keywords*:** semi-aerobic, landfill, SWOT analysis, alternative, solution, Indonesia

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1. INTRODUCTION

The issue of waste is one of the societal issues that are frequently present in cities all over the world. Due to increased production and consumption activities, which will result in more landfills, this issue is getting worse as the population grows. Waste management, which lacks waste management finances, management systems, waste management rules, and community involvement, is another factor in any city's waste issues. Additionally, improper trash management will lead to social issues like mob wrath, resident conflicts, and landfill blocking (Hendra, 2016).

Indonesia is one of Southeast Asia's largest economies and is bound to have residents with far higher living standards that will raise the production

and consumption of goods which will result in waste. Indonesia has encountered pressing problems in managing municipal solid wastes (MSW) (Aprilia, 2021). Municipal Solid Waste (MSW) is solid waste consisting of organic and inorganic materials considered useless and mostly from household consumption. With a total population of 272,682,500 people (Badan Pusat Statistik, 2022), Indonesia generates 68,390.71 tonnes/day of MSW in a total area of 1,916,906 km2.

Indonesia has numerous waste management plans. Waste is collected, sorted, reused, repurposed, and processed at TPST (Tempat Pengolahan Sampah Terpadu/Integrated Waste Management Site). It is sent to TPA (Tempat Pembuangan Akhir/Landfill) after processing by TPST (Christiani, 2021). The Waste Management Law No. 18 of 2008 requires that landfill at the Final Processing Site be controlled with a landfill control system or sanitary landfill. However, up to 35.46% of final disposal sites (TPA), according to data from the Ministry of Environment and Forestry (KLHK), were run in an open-dumping landfill until May 2022 (Puspa, 2022), because proper sanitary landfill concepts were not fully implemented.

Apart from the fact that the concept of sanitary landfills has not been fully implemented, the condition of landfills in Indonesia is already in an apprehensive direction. Indonesia has many landfills that are on the point of being overcapacity (Christiani, 2021). Waste overload in many landfills shows that landfills have polluted the environment a lot when they are not managed properly. This issue has led to environmental problems such as surface and groundwater pollution, emission of greenhouse gases (GHG), and odor nuisance.

Therefore, selecting a new landfill plan is essential, and it can operate with the bare minimum of equipment and infrastructure. Utilizing the old landfill as a profit-oriented landfill through implementing a landfill gas management or clean development mechanism project will help ensure future landfill capacity sustainability (Meidiana & Gamse, 2010). The Ministry of Public Works is currently developing different alternative landfill systems by developing landfill technology (Darwati, 2013).

So, this study aims to know why a semi-aerobic landfill must be one of the alternative solutions for Indonesian landfills and to evaluate the feasibility of implementing a semi-aerobic landfill system in Indonesia. The implementation of the semi-aerobic landfill system in Indonesia is still in the field-scale trial stage in several landfills so research is still needed on the semi-aerobic landfill system. With the development of semi-aerobic landfill technology, it can be another alternative solution to solve landfill and waste management problems.

2. METHODS

2.1. The Concept of the Semi-Aerobic Landfill

Semi-aerobic landfill system also known as the Fukuoka Method is an innovative landfill technology initially suggested by Dr. Masataka Hanashima, a current professor emeritus of Fukuoka University, and is a joint project of Fukuoka City with Fukuoka University and has been implemented in Japan since 1970 (JICA, 2010). It is a proven technology that has been tested in various locations around Japan as well as in a few Asian countries, such as Malaysia, Pakistan, China, Thailand, and Vietnam, as well as Samoa, the Dominican Republic, Mexico, Italy, and many others.

The Fukuoka method semi-aerobic landfill system is generally characterized as a system where the leachate and gas are continuously removed from the waste mass using leachate collection and gas venting systems with proper engineering designs in which the ambient air flows naturally into the waste body through the leachate collection pipes and subsequently improves the waste stabilization process and increases the leachate quality due to the enhancement of the micro-org (Chong et al., 2005). A controlled amount of air is introduced into the waste mass, creating an environment that promotes aerobic and anaerobic processes. This controlled ventilation accelerates the decomposition of organic waste, accelerates the decomposition of complex compounds, and reduces the production of methane, a potent greenhouse gas (dos Muchangos & Tokai, 2020). The semi-aerobic landfill mechanism can be seen in Figure 1.

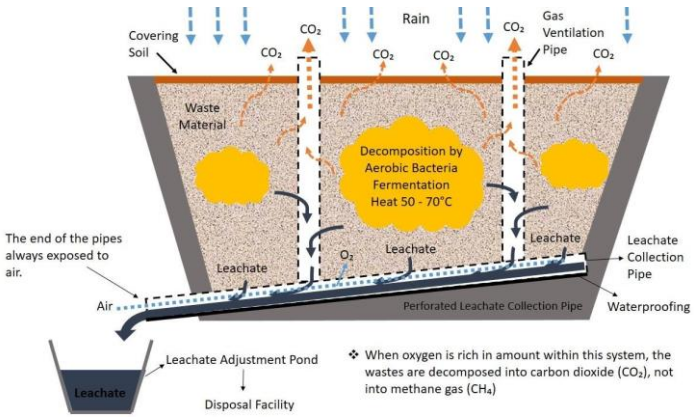

Figure 1. Semi-Aerobic Landfill Mechanism
(Reference: Fukuoka City Environmental Bureau JAPAN, 2013)

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2.1.1. The Reduction Effect of Greenhouse Gas

Methane is a potent greenhouse gas with a much higher warming potential than carbon dioxide, making its reduction a critical aspect of climate change mitigation efforts. Since methane contributes to global warming 21 times more than carbon dioxide, it is important to reduce methane production using the semi-aerobic landfill method. According to research, compared to an anaerobic landfill, a semi-aerobic landfill can minimize the impact of greenhouse emissions from the landfill by as much as 40% (JICA, 2010). Unlike anaerobic conditions found in conventional landfills, semi-aerobic systems promote aerobic decomposition, creating an environment less conducive (Yang et al., 2012). This shift in decomposition processes not only decreases methane generation but also facilitates the conversion of organic waste into less harmful byproducts. Additionally, semi-aerobic landfills often incorporate gas collection and recovery systems, allowing for the capture and beneficial use of the generated biogas, further mitigating the greenhouse gas impact (Fukuoka City Environmental Bureau, 2013).

There have been many studies on semi-aerobic landfills in various countries about the reduction effect of greenhouse gases. These studies are the improvement of carbon degradation rate, one order of magnitude higher than in anaerobic systems (Ahmadifar et al., 2016); (Cossu et al., 2003); (Zhang et al., 2019); the enhancement of nitrogen removal (Cossu et al., 2003); (P. He et al., 2011); (Shao et al., 2008); (Yang et al., 2012); (Zeng et al., 2006); the reduction of methane generation (Ahmadifar et al., 2016); (Huang et al., 2008); (Muenmee et al., 2016); (Morello et al., 2017); the reduction of emissions gas (Sutthasil et al., 2014); (Wu et al., 2017); (dos Muchangos & Tokai, 2020).

2.1.2. The Leachate Quality

The quality of leachate in semi-aerobic landfills is an important aspect when evaluating the environmental performance of this innovative waste management approach. Compared to traditional anaerobic landfills, semi-aerobic systems perform controlled aeration and therefore influence the composition of the leachate (Morello et al., 2017). Better waste decomposition conditions in semi-aerobic landfills often result in leachates with lower organic content and lower contaminant concentrations (S. Q. Aziz et al., 2010). This creates leachates that are less harmful to the environment, particularly in terms of groundwater contamination and soil degradation. One year after the semi-aerobic landfill structure was implemented, the quality of the leachate significantly improved with a significant decrease in BOD (Ministry of the Environment, 2012) Within a year, NH3-N showed a significant decrease. On the other hand, the anaerobic landfill barely decreases.

Studies on the effects of semi-aerobic landfills on leachate quality have been carried out in various countries. These studies are semi-aerobic bioreactor landfills (SABLs) that use bioreactors to improve traditional landfills (Morello et al., 2017); (Luo et al., 2019); (Ahmadifar et al., 2016); the qualities of leachate (Ma et al., 2021); (Huang et al., 2008); (S. Q. Aziz et al., 2010); the influence of landfill structures on stabilization of leachate (Zhang et al., 2019); (Yang et al., 2012); the advantages and mechanism of semi-aerobic landfill (Lavagnolo et al., 2018); (Grossule & Lavagnolo, 2020); (H. A. Aziz & Hosseini, 2012); (Y. He et al., 2012).

2.1.3. The Utilization of Completed Landfill

The utilization of completed landfills through the semi-aerobic landfill approach provides an innovative solution to the problem of reusing land that has reached its waste disposal capacity. Traditional closed landfills often remain dormant, and significant problems have been encountered, including subsidence, water pollution, and gas migration, posing environmental and spatial challenges (Aplet & Conn, 1977). However, the semi-aerobic landfill concept involves converting the completed site into a multi-functional and sustainable space. Compared to other landfills, semi-aerobic landfill technology stabilizes landfill sites more quickly and becomes stable in the early stage after completion the land has served its purpose as a landfill (Fukuoka City Environmental Bureau, 2013).

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2.2. An Overview of Indonesian Landfill

2.2.1. Open Dumping Landfill

The Ministry of Environment and Forestry (KLHK) noted that as many as 35.46% of landfills in Indonesia (TPA) were managed in an open dumping manner until May 2022 (Puspa, 2022). Due to the country's fast urbanization and insufficient facilities for waste disposal, open-dumping landfills have long been a common waste management method in Indonesia. Most landfills in Indonesia practice either open dumping or controlled dumping because proper sanitary landfill concepts are not fully implemented due to technological and financial constraints. These landfills are characterized by the indiscriminate and unregulated disposal of waste in open areas, often

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without any environmental safeguards or proper waste separation. There are several negative consequences of open dumping, such as as air pollution, pollution of groundwater, environmental deterioration, and health risks for humans. These sites are notorious for their unsightly appearance and the release of noxious odors, which pose threats to nearby communities and ecosystems.

The open dumping of waste is a complex issue in Indonesia, exacerbated by challenges such as insufficient funding, limited public awareness, and inadequate waste management policies and regulations. Addressing this problem requires comprehensive measures, including the development of sustainable waste management infrastructure, increased public awareness and education, and the enforcement of strict regulations to discourage open dumping practices. While open dumping remains a significant challenge, concerted efforts by the government, local communities, and environmental organizations are essential to transitioning toward more responsible and environmentally friendly waste management practices.

2.2.2. Overcapacity Landfill

The issue of landfills in Indonesia being on the verge of overcapacity is an increasing problem. Overcapacity landfills in Indonesia have emerged as a concerning waste management issue due to the country's rapid population growth and urbanization. There are serious environmental and health issues as a consequence of these landfills filling up above their designated capacity. The quantity of residual trash (waste that is difficult to recycle) that ends up in landfills in Indonesia is seen as out of balance given the country's poor recycling rate. This problem results in a significant accumulation of waste in landfills (Bahraini, 2022). Overcrowded landfills often result in improper waste disposal practices, such as open dumping, which further exacerbate the problem. Overcapacity landfills can cause groundwater and soil contamination, air pollution, disease-carrying vector attraction, and methane, a potent greenhouse gas emission.

According to Waste4Change, several landfills, including the Bantargebang landfill in Bekasi, West Java, the Suwung landfill in Denpasar, the Sarimukti landfill in Bandung, the Piyungan landfill in Yogyakarta, and the Terjun landfill in Medan, are also significantly at risk of becoming overcapacity (Christiani, 2021). Furthermore, other locations are frequently located close to heavily resided areas, which puts the health and welfare of the people living there around at danger.

2.2.3. Greenhouse Gases Emissions from Landfill

Greenhouse gas emissions from Indonesian landfills pose serious environmental problems as landfills become a major source of methane, a greenhouse gas that contributes to global climate change. Compared to other sectors, emissions from the waste sector are relatively low but mainly contribute to methane (CH4) and nitrous oxide (N2O) emissions. This problem is further exacerbated by the country's urbanization and population growth, which is leading to an increase in the amount of organic waste. Improper waste management practices, such as open dumping and limited gas recovery systems, further exacerbate this problem. Uncontrolled methane emissions not only accelerate climate change but also cause local air pollution and impact the health and well-being of local communities. According to BPS (2020), Indonesia's waste sector produces 127 billion tons of CO2 in greenhouse gas emissions (Aprilia, 2021).

Figure 2. The Utilization of Imazu Landfill Site
(Reference: Fukuoka City Environmental Bureau JAPAN, 2013)

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2.3. Previous Studies on Semi-Aerobic in Indonesia

There have only been a few studies on semi-aerobic systems in Indonesia, and only trials have been conducted on the reliability of implementing semi-aerobic landfills in Indonesia. However, there is no further discussion on the implementation of semi-aerobic systems in Indonesia. The previous studies on semi-aerobic landfill systems in Indonesia, which can be seen in Table 1.

Previous research from other nations provides a solid foundation for the implementation and improvement of semi-aerobic landfill technology. This approach can address Indonesia's waste management challenges by aligning with environmental and sustainability goals. However, continued research and practical application are essential to realizing the benefits of semi-aerobic discharge and ensuring its successful integration into Indonesia's waste management infrastructure

3. RESEARCH METHOD

This research used a qualitative approach based on collecting, analyzing, and interpreting data in the form of narratives and visuals (not numbers) to gain an in-depth understanding of semi-aerobic systems (Susanto, 2013). Secondary data collection used in this study was carried out by library research or literature study, which is data collection using literature in the form of literature or references, similar research reports, seminars, or journals. The data in this study was taken from literature sources that emphasized literature reviews, such as journals, articles, books, and documentation from government regulations from Indonesia and Japan related to semi-aerobic landfills and waste management systems (Yosep & Ayunda, 2021). The data is also obtained from various research results from previous research. The main source of this research literature review is A Practical Guide to Landfill Management in Pacific Island Countries and Territories, Volume 1: Inland-based Waste Disposal in Chapter 3: Basic Concepts of Semi-Aerobic Landfill; and The Fukuoka Method.

The data obtained from the literature review was then analyzed with a SWOT analysis. SWOT analysis used in this research is a strategic planning method used to evaluate strengths, weaknesses, opportunities, and threats in a semi-aerobic landfill. The SWOT analysis includes the systematic identification of various factors to formulate management strategies based on a logic that can maximize strengths and opportunities while simultaneously minimizing weaknesses and threats (Muta'ali, 2015). In qualitative, after knowing and analyzing descriptively the SWOT elements, the output will be in the form of a SWOT matrix that will determine whether semi-aerobic landfills can be used as alternative solutions for Indonesian landfills and evaluate the feasibility of implementing the semi-aerobic landfill system method in Indonesia.

4. RESULT AND DISCUSSION

4.1. SWOT Analysis

This section shows the primary results of the SWOT analysis. Strengths and weaknesses are mostly tied to internal conditions of the semi-aerobic landfill, whereas opportunities and threats are related to external factors of the semi-aerobic landfill in Indonesian waste management. The SWOT analysis of the primary results is summarized in Table 2.

Table 1. Previous Researches of Semi-Aaerobic Landfill in Indonesia

No	Title	Author	Research Result
1	Kinerja Penimbunan Sampah Sistem Semi Aerobik Landfill Sebagai Bahan Masukan Penyusunan Standar Landfill (*Performance of Semi-Aerobic Landfill as inputs for Landfill Standard*)	(Darwati, 2013)	The research discusses the implementation of semi-aerobic landfilling as a controlled waste management system in compliance with waste management regulations. Research shows that, as compared to anaerobic landfilling, semi-aerobic landfilling produces leachate with higher quality and lower methane gas emissions. The cost of implementing semi-aerobic landfilling is noted to be 1.3 times more expensive than anaerobic landfilling due to the construction of larger leachate pipes. Key criteria for designing semi-aerobic landfilling include the amount of air and leachate in the collecting pipe, topographical considerations for leachate outflow, and the construction of leachate collection tanks. The research emphasizes how city waste management operators must have standards and resources when implementing controlled landfill systems.
2	New Landfill System in North Kolaka Regency, Southeast Sulawesi, Indonesia	(Rahim & Djamaluddin, 2017)	The research discusses the Fukuoka semi-aerobic landfill system, which was implemented in North Kolaka Regency, Southeast Sulawesi, Indonesia, to solve the problems related to open dumping and open burning in developing countries. The research states that the estimated capital costs are based on the assumption that the landfill site has naturally low-permeability clay soil, negating the need for a synthetic or geomembrane liner, which, if necessary, may dramatically raise overall costs. The study analyzes and shows the total disposal costs per ton of waste, which is projected to be 469,431 tons at the landfill site. The conclusion of the study suggests that the Fukuoka semi-aerobic landfill system is a viable method for use in developing countries like Indonesia, despite the relatively higher overall cost per ton of waste compared to existing average tipping fees in some major cities, due to its ability to mitigate negative environmental impacts.

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Table 2. Results of SWOT Analysis on Semi-Aerobic Landfill

Internal Factor	
Strength	Weakness
• Leachate quality in semi-aerobic landfill is better than in anaerobiclandfill • Low emission of greenhouse gases toreduce air pollution and global warming • Less underground water pollution fromleachate • Life-cycle cost is less expensive than that of an anaerobic system • Technology is simple and easy tomaintain if the concept is fully understood • Landfill stabilizes faster than anaerobictype	• Semi-aerobic landfill construction cost are more expensive than anaerobic systems • People who will operate a semi-aerobic landfill system must be familiar with and understand the technology • There are still not many studies ontropical countries
External Factor	
Opportunity	Threat
• Semi-aerobic landfill system is a viable method to be used in developing countries • Another alternative solution in waste management • Might turn into a landfill for-profit purposes • May be able to deal with Indonesia'slandfill issues • Use of the private sector to Invest in Landfill Projects	• There are still not many areas in Indonesia that use semi-aerobic landfill systems • There are s-dumping activities inseveral landfills • Risk of Overcapacity Landfill • One of the greenhouse gas producers inthe waste sector • Lack of awareness regarding the waste problem and the serious damage to theenvironment it has brought about

Source: Author's Analysis Result

4.1.1. Strengths

A semi-aerobic landfill is one where waste undergoes the process of decomposition while being exposed to oxygen. This method of landfilling waste has various advantages, including a decrease in landfill gas and a quicker stabilization of the material that is dumped. Leachate quality increases significantly and more quickly than in anaerobic landfills, possibly resulting in a large decrease in leachate treatment costs. As a result of the landfill stabilizing more quickly, less methane is produced, which helps to slow the effects of global warming. The landfill also stops settling more quickly, allowing the finished landfill site to be put to other uses.

4.1.2. Weakness

Previous studies have led to the conclusion that semi-aerobic landfill systems are a practical solution for usage in developing countries such as Indonesia. However, not much research has been carried out in tropical countries. Early on in a semi-aerobic landfill system's development, the diameter of the leachate pipe in the semi-aerobic landfill system necessitates high building costs. Additionally, someone who is very educated about technology is required to operate a semi-aerobic landfill system for it to function correctly.

4.1.3. Opportunities

A semi-aerobic landfill can be an alternative solution for Indonesia's landfill issues, solving the problems of overcapacity landfills and open dumping landfills in urban areas. Semi-aerobic landfills offer effective solid waste management and have great promise to improve sustainability and be more environmentally friendly. Semi-aerobic landfills can turn old landfills into profit-oriented landfills, which will help ensure the sustainability of landfill capacity in the future. Additionally, semi-aerobic landfills can draw in the corporate sector to work with governments to create semi-aerobic landfills.

4.1.4. Threats

The semi-aerobic landfill has not been implemented in Indonesia, and not much research has been done. In addition, many landfill-related issues in Indonesia must be solved, including the risk of overcapacity landfills and open-dumping activities. Compared to other sectors, emissions from the waste sector are relatively low but are a major contributor to emissions of greenhouse gases, which makes Indonesia a producer of greenhouse gases. Indonesia also has a tropical environment, so the implementation of a semi-aerobic landfill could have an impact on how well the landfill operates. The performance of the degradation process, as well as leachate and biogas management, could be significantly impacted by dry seasons with low humidity and wet seasons with high rainfall. However, Indonesians' awareness of waste is still low. Changing the Indonesian community's perceptions of waste is the hardest thing to do. There are still a lot of Indonesians who throw away their trash carelessly, which contributes to pollution.

4.2. SWOT Matrix

This section shows the SWOT matrix that can be found in Table 3. The matrix is an important tool of SWOT analysis for selecting decision-making for semi-aerobic landfill systems as an alternative solution to Indonesia's landfill issues. This will lead to exploiting the benefits, improving the weaknesses, exploiting opportunities, and reducing threats.

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Table 3. SWOT Matrix

	STRENGTH	WEAKNESS
OPPORTUNITY	SO: - Alternative solutions - Suitable for developingcountry - Making use of the completed landfill - Leachate as an energy source[1]	WO: - Improving human resourcesin waste management - Increasing both governmental and private sector involvement in the initial investment of semi-aerobic landfills.
THREAT	ST: - Improve landfillconditions - Reduce pollution - Improve public awareness of waste among citizens	WT: - Promoting the developmentof semi-aerobic landfills byempowering local governments and communities - For the further research

Source: Author's Analysis Result

According to the SWOT matrix, the following solutions could be implemented:

4.2.1. Strengths–Opportunities Strategies:

- Alternative Solution

Semi-aerobic landfills present a promising alternative for addressing the pressing waste management challenges faced by Indonesia. With a rapidly growing population and urbanization, the country is grappling with mounting waste disposal issues, including limited landfill space, environmental degradation, and health hazards. Semi-aerobic landfills can offer a sustainable solution to these problems. These landfills, which combine aspects of aerobic and anaerobic decomposition, provide a more efficient and environmentally friendly approach to waste management. By incorporating controlled aeration, they promote better waste decomposition and significantly reduce the generation of methane, a potent greenhouse gas. This not only mitigates the contribution of landfills to climate change but also minimizes odors and the attraction of disease-carrying vectors, making landfill sites more suitable for neighboring communities.

Furthermore, semi-aerobic landfills encourage better waste segregation and recycling practices, extending the lifespan of these facilities and reducing the need for continuous expansion. This, in turn, saves on costs associated with landfill operation and maintenance. In a country like Indonesia, where waste management infrastructure and policies are continually evolving, semi-aerobic landfills represent a forward-thinking approach to curbing environmental pollution and promoting a more sustainable waste management system. By adopting and scaling up semi-aerobic landfill technology, Indonesia has the potential to address its landfill capacity issues, reduce pollution, and provide a healthier and safer living environment for its citizens.

- Suitable for Developing Country

Semi-aerobic landfills offer a compelling solution that is particularly suitable for developing countries like Indonesia facing significant waste management challenges. With a growing population and urbanization, many developing nations grapple with limited landfill space, environmental degradation, and health hazards stemming from inadequately managed waste. Semi-aerobic landfills present a sustainable and cost-effective approach to addressing these issues. One key advantage is that semi-aerobic landfills do not require the same level of engineering and operational complexity as advanced sanitary landfills, making them a more accessible and affordable option for developing countries. The technology can be implemented with relatively modest infrastructure and operational requirements, reducing the financial burden on local municipalities and waste management authorities.

Moreover, the reduction of methane emissions in semi-aerobic landfills has the potential to positively impact climate change mitigation efforts in these countries. By capturing and converting methane into a less harmful form, semi-aerobic landfills align with international environmental goals. Semi-aerobic landfills also encourage better waste segregation, recycling, and waste reduction practices, which can contribute to more efficient landfill operations and prolong the facility's lifespan. This is particularly valuable in developing countries where land scarcity and limited resources necessitate the optimization of existing landfill sites.

- Making use of the Completed Landfill

The idea of reusing completed landfills is an approach that utilizes previously unused landfill sites while addressing environmental and resource issues. Once a landfill reaches its maximum capacity and is officially closed, it often becomes unused and underutilized. But by turning these locations into multifunctional spaces, communities can unlock untapped potential. Semi-aerobic landfill technology makes the stabilization of the landfill faster and more stable. The site can then be transformed into a park, green space, renewable energy facility, or even a solar energy facility. This approach not only maximizes land use but also promotes environmental sustainability, community welfare, and renewable energy production. The use of completed landfills demonstrates responsible land management for the benefit of local communities and the environment.

[1] In (Singh et al., 2023), (Kurniawan et al., 2021), (Moustakas et al., 2020), (Iskander et al., 2016) & (Yong et al., 2019)

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- Leachate as an Energy Source

Leachate is a liquid byproduct created when water interacts with decaying waste in a landfill and can be used as a valuable source of energy. There are many pollutants, including dissolved organic and inorganic pollutants, heavy metals, and other NH3-producing chemicals, that are present in landfill leachate, and microbial fuel cells (MFCs) are a better approach to nutrient removal from leachate as they increase the removal efficiency as well as generate electricity ((Singh et al., 2023) & (Kurniawan et al., 2021)). Another method is anaerobic digestion, a biological process in which microorganisms break down organic materials in the absence of oxygen. Through this process, the leachate is converted into biogas, more precisely methane, which can then be recovered and used as a renewable energy source (Moustakas et al., 2020).

Bioelectrochemical systems (BES) have been studied recently to produce electricity using landfill leachate as a substrate. Although BES is an effective method to treat leachate, there are still prospects for resource recovery from leachate because of its special ability to generate bioelectricity (Iskander et al., 2016). Waste-to-energy (WTE) technology is an energy recovery method that transforms waste residual chemicals into useful energy sources like steam, heat, or electricity from non-recyclable waste while reducing the solid waste biodegradable fraction to zero (Yong et al., 2019).

There are many methods for converting leachate into energy. Leveraging leachate as an energy resource exemplifies a creative and sustainable approach to waste management, simultaneously addressing environmental concerns and contributing to the generation of clean energy in Indonesia. Continued research and technological advancements in this field hold the promise of further optimizing the energy potential inherent in leachate from landfills. Collaborative efforts involving government initiatives, private sector investments, and research institutions are crucial to unlocking the full potential of leachate-to-energy projects in Indonesia. By transforming a waste byproduct into a renewable energy resource, Indonesia can make significant strides towards more sustainable and integrated waste management practices.

4.2.2. Strengths–Threats Strategies

- Improve Landfill Conditions

Semi-aerobic landfills have the potential to substantially improve landfill conditions compared to traditional, anaerobic landfill systems. The controlled introduction of air into semi-aerobic landfills allows for better waste decomposition and reduces the formation of noxious gases, such as methane, which are typically associated with anaerobic decay. This leads to a notable decrease in unpleasant odors and the attraction of disease-carrying vectors, greatly enhancing the overall environmental quality in and around the landfill site.

In addition, the improved waste decomposition in semi-aerobic landfills contributes to the reduction of leachate production and leachate pollution. The leachate, a liquid byproduct of decomposing waste, is more easily managed and treated in these systems, which helps prevent groundwater contamination and facilitates more effective leachate collection and treatment processes. Semi-aerobic landfills also encourage better waste segregation and management practices, promoting recycling and waste reduction. This, in turn, extends the lifespan of the landfill by decreasing the volume of waste that needs disposal. This not only leads to cost savings but also minimizes the environmental impact associated with landfill expansion.

- Reduce Pollution

Semi-aerobic landfills offer significant potential to reduce pollution and mitigate the environmental harm associated with traditional landfills. These innovative waste management facilities incorporate a controlled level of aeration, which promotes more efficient decomposition of organic waste, reducing the emission of methane, a potent greenhouse gas. By capturing and converting methane into a less harmful form, semi-aerobic landfills mitigate one of the most significant contributors to climate change and air pollution.

Moreover, semi-aerobic landfills typically employ advanced leachate management systems to prevent the contamination of surrounding soil and groundwater. This proactive approach minimizes the risk of water pollution and the release of harmful chemicals into the environment, further enhancing the reduction of pollution. In addition, the minimized odors and reduced vector attraction associated with semi-aerobic landfills contribute to a healthier and more pleasant living environment for nearby communities. This is particularly important in densely populated areas where pollution control is a significant concern.

- Improve Public Awareness of Waste Among Citizens

Improving public awareness of waste management is an essential step toward fostering responsible environmental stewardship among citizens. Enhanced understanding of waste-related issues, such as recycling, proper disposal, and the consequences of irresponsible waste management, can lead to more conscientious behavior and a reduced environmental impact. Education and outreach programs are key tools for raising public awareness. By providing accessible information about waste management practices and their environmental significance, communities can empower individuals to make informed choices. These programs can be delivered through schools, community workshops, online resources, and public campaigns, encouraging citizens to adopt sustainable waste practices.

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Furthermore, engaging citizens in the process by promoting recycling and waste reduction initiatives encourages active participation. Hands-on experience with eco-friendly practices not only reduces the waste stream but also reinforces the importance of responsible waste management. Media, social platforms, and public service announcements can also play a significant role in shaping public awareness and opinion. These channels can disseminate information about waste management issues, highlight success stories, and drive home the message that individual actions can collectively make a substantial difference in preserving the environment.

4.2.3. Weaknesses–Opportunities Strategies

- Improving Human Resources in Waste Management

The most important factor in getting the landfill to run smoothly is its personnel. Improving human resources in waste management, particularly in the context of semi-aerobic landfills, is a vital component of ensuring the successful implementation and sustainability of these innovative waste management solutions. As semi-aerobic landfills combine elements of both aerobic and anaerobic decomposition, it is essential to equip the workforce with the necessary knowledge and skills to operate and manage these facilities effectively.

One key aspect of enhancing human resources is providing comprehensive training and education to landfill operators and staff. This includes instruction on waste segregation, proper waste handling, health and safety protocols, and the technical aspects of semi-aerobic landfill operation. Training programs can help mitigate potential environmental risks and ensure the safety of workers as well as the surrounding communities.

Moreover, investing in the professional development of waste management personnel is essential for optimizing the efficiency and environmental performance of semi-aerobic landfills. Keeping staff informed about best practices, emerging technologies, and regulatory updates empowers them to make informed decisions and adapt to changing waste management requirements. Furthermore, promoting a culture of continuous improvement and innovation among waste management professionals can lead to the development of more sustainable and cost-effective waste management practices. Encouraging research and knowledge sharing within the industry can foster creative solutions and drive improvements in semi-aerobic landfill operations.

- Increasing Both Governmental and Private Sector Involvement in the Initial Investment of Semi-Aerobic Landfills

Semi-aerobic landfill construction costs are expensive, so the government must improve the budget to implement semi-aerobic landfills to improve landfill conditions. Increasing both governmental and private sector involvement in the initial investment of semi-aerobic landfills is a strategic move that can accelerate the adoption of this innovative waste management technology. Governmental agencies, at various levels, have a critical role to play in providing the necessary financial support and regulatory framework for semi-aerobic landfill projects. By allocating funds, offering incentives, or establishing partnerships with private investors, governments can significantly reduce the financial burden on local municipalities and waste management authorities. This, in turn, makes it more feasible for communities to embrace semi-aerobic landfill technology, which offers both environmental and economic benefits.

Simultaneously, encouraging private sector involvement can bring valuable expertise, efficiency, and innovation to semi-aerobic landfill projects. Private investors, waste management companies, and technology providers can contribute financial resources, technological know-how, and operational experience to ensure the success of these initiatives. Public-private partnerships can facilitate the design, construction, and operation of semi-aerobic landfills, leveraging the strengths of each sector to create sustainable and economically viable waste management solutions.

By increasing both governmental and private sector involvement in the initial investment of semi-aerobic landfills, we can expedite the transition to more environmentally responsible and cost-effective waste management practices. This collaborative approach benefits not only the environment but also local communities and the broader economy by promoting sustainable waste disposal and potential energy recovery.

4.2.4. Weaknesses–Threats Strategies

- Promoting the Development of Semi-Aerobic Landfills by Empowering Local Governments and Communities

Promoting the development of semi-aerobic landfills through the empowerment of local governments and communities is a strategic approach with significant potential to transform waste management practices. Local governments play a pivotal role in shaping waste management policies and infrastructure, making them key drivers of change. Empowering these entities involves providing them with the knowledge, resources, and incentives needed to adopt and implement semi-aerobic landfill technologies.

One of the crucial steps is raising awareness among local government officials and decision-makers about the benefits of semi-aerobic landfills, such as reduced environmental impact, improved waste decomposition, and potential energy recovery. Equipped with this understanding, local governments can prioritize the adoption of these technologies and incorporate them into their long-term waste management plans. Community involvement and education are equally vital. Empowering communities

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with information about semi-aerobic landfills, their benefits, and the importance of proper waste disposal can lead to more responsible waste practices. This can include initiatives such as recycling programs, source separation, and waste reduction strategies, which can complement the semi-aerobic landfill approach.

Moreover, collaboration between local governments and communities can foster more inclusive and sustainable waste management solutions. Participatory decision-making processes can ensure that local needs, concerns, and values are integrated into landfill planning and operations. This not only enhances the social acceptance of semi-aerobic landfills but also facilitates smoother implementation. Financial incentives and support from higher-level governments can further empower local authorities to invest in semi-aerobic landfill projects. Grants, subsidies, or tax incentives can make these technologies more financially feasible, allowing local governments to allocate resources effectively.

- For the Further Research

Further research in semi-aerobic landfills in Indonesia deserves attention, and exploration presents a compelling avenue for enhancing waste management practices and environmental sustainability. A comprehensive analysis of the economic viability and scalability of technologies is essential. Understanding these systems' costs and potential revenue streams is crucial for decision-makers and investors. This research should also consider the long-term sustainability of such projects. The environmental impacts need thorough examination, including assessing any potential secondary pollution, emissions, or ecological consequences associated with these processes. Understanding the broader environmental footprint will help develop more environmentally friendly and sustainable systems.

Moreover, developing innovative and efficient technologies should be a focus for further research. Improving the conversion efficiency of biogas production or investigating emerging technologies can help make these processes more competitive and environmentally friendly. The case studies and real-world implementations of semi-aerobic landfills in Indonesia, including their successes and challenges, can serve as valuable sources of knowledge. These practical experiences can offer insights into best practices, technology deployment, and community engagement.

4.3. Feasibility of A Semi-Aerobic Landfill System in Indonesia

From the SWOT analysis and SWOT matrix, several factors that determine the feasibility of a semi-aerobic landfill system in Indonesia can be seen in Figure 3 below.

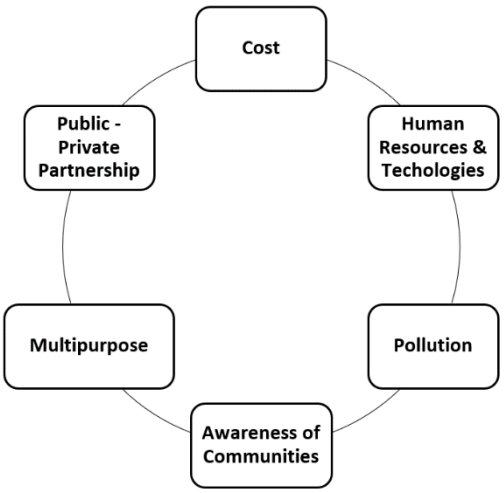

Figure 3. Feasibility of A Semi-Aerobic Landfill System in Indonesia
References: Author's Analysis Result

- Cost; although the initial cost of building a semi-aerobic landfill system is expensive, it can be a long-term waste management plan that can be profitable and has many advantages that are suitable for developing countries like Indonesia.
- Human Resources & Technologies; the technology used in semi-aerobic landfill systems must be well understood because it is critical for successful implementation and sustainability; thus, improving human resources in waste management and technology, particularly in semi-aerobic landfills system, is necessary.
- Pollution; pollution reduction is the biggest advantage of semi-aerobic landfill systems to reduce pollution in the world, especially in Indonesia.
- Awareness of Communities; community awareness on waste management is crucial for sustainable practices, promoting responsible disposal, recycling, and consumption, and fostering a culture of environmental stewardship and conservation.
- Multipurpose; in addition to reducing pollution, semi-aerobic landfill systems have many other benefits, making them a multipurpose landfill for waste management solution in Indonesia.
- Public-Private Partnership; by increasing government and private sector participation in initial investments in semi-aerobic landfills, Indonesia can accelerate the transition to more environmentally friendly and cost-effective waste management practices.

5. CONCLUSION

From the general findings of this study, it can be concluded that semi-aerobic landfills are an innovative solution for reducing pollutants and developing a more sustainable waste management system in a country like Indonesia. Based on the results of the SWOT matrix, the implementation of

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semi-aerobic landfill technology in Indonesia holds substantial promise for addressing the country's pressing waste management challenges in an environmentally sustainable manner. By adopting and implementing semi-aerobic landfill technology, Indonesia has the potential to address its landfill capacity issues, reduce pollution, and provide a healthier and safer living environment for its citizens. Besides that, the feasibility of a semi-aerobic landfill system in Indonesia is determined by factors such as cost, human resources, pollution reduction, community awareness, multipurposeness, and public-private partnerships, which can accelerate the transition to environmentally friendly waste management practices.

Future research in semi-aerobic landfills offers opportunities to refine and optimize this waste management approach. By exploring design improvements, advanced monitoring systems, long-term performance assessments, and comparisons with conventional landfills, we can advance our understanding of semi-aerobic landfill operations and their potential for more sustainable waste management practices. It is recommended that further efforts to prepare a more comprehensive analysis be carried out from time to time if necessary so that the semi-aerobic landfill can be an alternative solution to the landfill system to improve waste management at the landfill site.

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