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A COMPARATIVE ANALYSIS OF LANDFILL PRACTICE BETWEEN POLAND AND INDONESIA

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ABSTRACT

This research addresses the global challenge of waste management (WM) by comparing landfill management practices in Poland (Radiowo landfill) and Indonesia (Kebon Kongok landfill) to define the differences in landfill WM systems and analyse the main challenges in implementing effective landfill management WM systems in Poland and Indonesia. The data was analysed by employing the rapid impact assessment matrix (RIAM). The analysis focused on three critical areas: gas management, leachate management and landfill reclamation. The results showed that the Polish landfill demonstrated high efficacy, particularly in leachate management with water quality impact (96), gas emissions control with methane extraction (96) and site reclamation for site restoration (96). For these purposes, the landfill uses advanced leachate treatment technologies and drainage systems. Conversely, Indonesian landfill practices show severe inefficiencies, with negative scores in almost all sectors. The lowest score was in leachate management with water quality impact (–48), gas emissions with air quality impact (–48) and site reclamation in community space development (–48). The study contributes to the sustainable waste management discourse, providing actionable insights for policymakers and environmental managers.

Keywords: landfill management, RIAM, gas management, leachate management, reclamation

INTRODUCTION

Waste management (WM) and disposal have emerged as critical global economic and environmental issues (Awino & Apitz, 2024). The increasing volume of waste generated in most countries signifies a growing challenge that demands immediate attention. This increasing trend can be attributed to various factors, including population growth, urbanisation, industrialisation and changing consumption patterns – particularly in developing countries (Kumari & Raghubanshi, 2023). Improper WM practices have significant consequences, leading to environmental pollution, soil degradation, water contamination, and air pollution (Ziraba, Haregu & Mberu, 2016; Abubakar et al., 2022; Mor & Ravindra, 2023; Sharma, Kaur & Aditya, 2023). Therefore, effective WM practices are paramount for addressing the environmental challenges of increasing municipal solid waste (MSW) generation levels.

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Poland has one of the lowest per capita MSW generation rates in Europe (Koc-Jurczyk, 2023). According to Statistics Poland and the National Waste Plan 2023 of Poland in Ciula, Bajdur, Gronba-Chyła and Kwaśnicki (2023), approximately 39.8–40% of MSW was disposed of in landfills in 2020 and 2021. As Poland's waste management practices are evolving towards sustainability, landfill reclamation emerges as a crucial element of WM because landfills pose significant environmental threats, such as soil and groundwater contamination by heavy metals, self-heating and spontaneous combustion, leading to fires, harmful emissions and the release of particulate matter, microorganisms and toxic compounds (Szulc et al., 2022). One of the landfills in Poland that has successfully implemented landfill reclamation is the Radiowo landfill. In contrast, Indonesia's WM system currently focuses on collecting, transporting and dumping waste in designated final disposal sites (FDS) areas. Unfortunately, many of these FDS rely on open dumping, causing severe environmental problems like soil, water and air pollution (Luthfiani & Atmanti, 2021).

As a developing nation, Indonesia faces challenges in implementing the best WM practices. However, the country has taken a step forward by enacting the 2008 WM Law, which requires all provinces to switch from open dumping to sanitary landfills. Open dumping is defined as a location where solid wastes are thrown away in a way that does not safeguard or protect the area, is susceptible to open burning and is accessible to local vectors and scavengers (Yasin & Usman, 2017). Meanwhile, sanitary landfills involve burying or covering waste to accelerate decomposition and prevent fires and disease (van Wee & Witlox, 2021). Despite these regulations, around 66.81% of landfills in Indonesia still implement open dumping systems because WM is not yet a priority for local governments, coupled with regional management funds still being below 1% of total regional expenditure.

The Indonesian province of Nusa Tenggara Barat (NTB) exemplifies the pressing need for improved WM practices nationwide. Recognising the severity of the issue, NTB passed Regional Regulation No 5 of 2019, which focused explicitly on WM strategies. Data from the Department of Environment and Forestry of NTB reveals a discrepancy between waste generation and proper management. In 2023, NTB produced roughly 3.9 million tonnes of waste. However, only 1.9 million tonnes were processed or disposed of in designated final disposal sites, which signifies a significant amount of waste – approximately 2 million tonnes, needing better management (Khalid & Agreista, 2023). Improper landfill management practices further complicate the issue, posing a severe environmental threat (Winahyu, Hartoyo & dan Syaukat, 2019; Emalya, Munawar, Rinaldi & Yunardi, 2020). A concerning report by Inside Lombok (2022) highlights the environmental consequences of the oldest and biggest landfill in NTB, which is the main object of this study, namely Kebon Kongok. It has experienced multiple problems – from organic pollution caused by gas generated by the municipal solid waste (MSW) to leachate contamination of groundwater. Immediate action is needed to prevent environmental damage and safeguard ecosystems, biodiversity and human health – especially in the face of rising global MSW generation (Abubakar et al., 2022; Awino & Apitz, 2024).

The WM is a comprehensive framework of strategies and procedures designed to identify, control and handle all types of waste. This framework encompasses the entire waste lifecycle, from its initial generation to final disposal, to minimise waste production, prevent improper disposal and ensure safe and responsible handling through collection, transportation, treatment and disposal methods (Mubasalat, 2021). Meanwhile, Bacinschi, Rizescu, Stoian and Necula (2010) identify WM as the process of handling discarded materials and plays a critical role in safeguarding public health and the environment. The complexity of landfills is increasing, and many aspects may affect emissions into the air that are poorly documented today (Rim-Rukeh, 2014). For instance, the EU Directive on waste landfills has introduced specific goals for reducing the volume of disposed waste and stringent requirements for landfilling and landfill sites by encompassing activities like monitoring waste generation, collecting it from its source, transporting it to designated facilities and processing it through recycling or responsible disposal. Effective WM minimises the negative impacts of waste on surrounding areas and promotes resource recovery through recycling (Vaverková, 2019).

There are three crucial factors resulting from the generation of MSW in landfills. The first is the formation of leachate, which contains a high concentration of pollutants that can contaminate bodies of water (Tchobanoglous & Kreith, 2002). According to Vaverkova (2019), leachate is formed through complex physical, chemical and biological interactions between waste products, moisture and external influences. The quality and quantity of leachate are influenced by factors such as waste composition, waste characteristics, landfill age, landfill operational practices and the amount of water that seeps into the landfill, including the volume of rainfall (Vaverková, 2019; Zhao, Liu, Feng, Li & Li, 2021). Second, the formation of gas in landfills (LFG) is a result of numerous field studies conducted worldwide to confirm that LFG has significant contributions to global greenhouse gas emissions (Fourie & Morris, 2004). Landfill gas (LFG), consisting primarily of methane (50–60%) and carbon dioxide (40–50%), is created by waste disposal facilities that receive organic waste as a result of biological, chemical and physical processes occurring in the landfill (Scheutz & Kjeldsen, 2019).

The third important factor is landfill reclamation, which restores and repurposes closed landfill sites for beneficial use, such as parklands or renewable energy installations (Veleva et al., 2017). The process of landfill reclamation is a promising solution to the challenges posed by rapid urbanisation in our society (Liu et al., 2023). Reclaiming land involves various tasks, including shaping the landfill, installing a degassing system, sealing the surface, implementing drainage and adding a layer of soil and vegetation (Koda, Podlasek, Osiński, Markiewicz & Vaverková, 2021). Reclamation is a long-term process that involves protecting waste landfills from harmful environmental effects and integrating them with the surrounding area. It can take more than a decade and must be done following a schedule specified in the consent to close the landfill (Majewski, 2021).

Therefore, driven by the three essential factors of generating MSW to the landfill, this research aims to: (i) define how LGM from MSW differs between Poland and Indonesia and what factors contribute to these differences; (ii) analyse the main challenges in implementing effective leachate management in landfill WM systems in Poland and Indonesia; (iii) determine the difference in the process of reclamation between Poland and Indonesia

MATERIAL AND METHODS

Materials

This study explores landfill management practices in two contrasting locations: the Radiowo landfill in Poland (Fig. 1a) and the Kebon Kongok landfill in Indonesia (Fig. 1b). According to Koda et al. (2022), the Radiowo landfill is the largest in Poland and is located near Warsaw. Radiowo is a sanitary landfill with an embankment style, covering approximately 20 ha and reaching a height of approximately 60 m. It served as the disposal site for Warsaw's MSW from the early 1960s until 1991, receiving all MSW from non-composted and composted materials. The landfill handled around 600 tonnes of waste daily, resulting in approximately 300 tonnes of non-composted waste. Finally, the reclamation project was conducted from 1999 to 2017 (Table 1).

On the other hand, the Kebon Kongok landfill in Indonesia is located in Nusa Tenggara Barat (NTB), West Lombok. Kebon Kongok has been operational since 1993 and covers an area of around 13 ha, with a designated capacity of 991,800 m^3. In 2021, the landfill had reached its maximum capacity (Table 1). However, it still receives 300–400 tonnes of waste daily from Mataram City and West Lombok (Khalid & Agreista, 2022). The landfill implements various waste management activities, including waste sorting, supervision, equipment operation, recycling, leachate management, biogas handling, buffer zone creation and even the utilisation of scavengers and black soldier fly larvae (*Hermetia illucens*) for waste processing (Alawiyah, 2016).

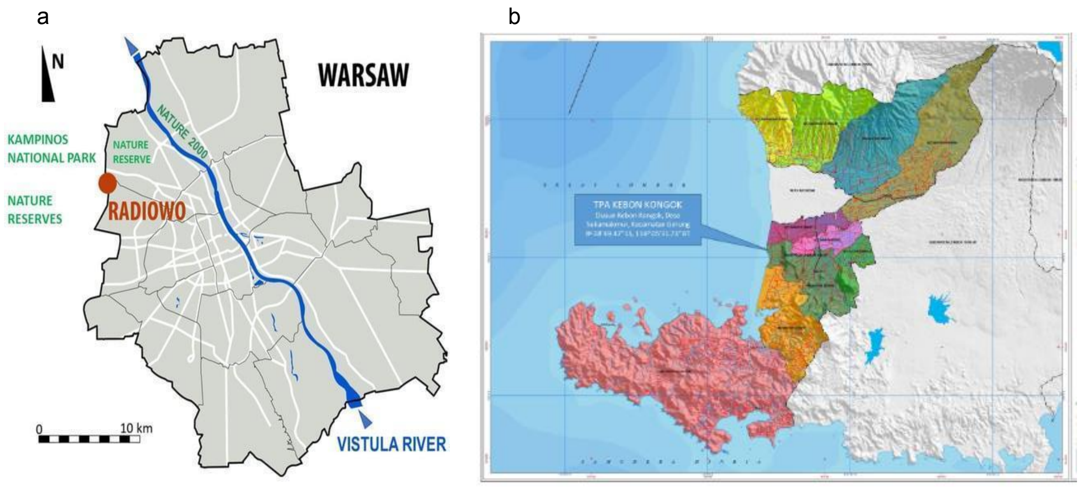

Fig. 1. Location map of Radiowo landfill in Poland (a) and Kebon Kongok landfill in Indonesia (b)

Source: [a]Koda et al. (2022); [b]Department of Environment and Forestry of West Nusa Tenggara province (2022).

Table 1. Summarised of important elements from Kebon Kongok landfill and Radiowo landfill

Specification	Kebon Kongok landfill	Radiowo landfill
Landfill type	open dumping	sanitary landfill
Area	13 ha	20 ha
Operation year	1993–present	1999–2017
Type of MSW	– biodegradable and non-biodegradable materials – hazardous household waste like batteries, paints and chemicals	– non-composted materials like plastics, textiles, glass and debris – composted materials
Types of WM activities type	– waste sorting – recycling – leachate management – biogas handling – scavengers and black soldier fly (*Hermetia illucens*) larvae for waste processing	– leachate management – gas management – reclamation
Climate	dry and rain seasons	four seasons: winter, spring, summer and autumn

Source: own work.

METHODS

This study employs both qualitative and quantitative approaches. The qualitative approach relies primarily on non-numerical data and direct observation (Crang, 2002). The quantitative approach uses the RIAM method to conduct a comprehensive comparison of landfilling practices in two countries. The study employs the RIAM method, specifically the Rapid Impact Assessment Matrix as shown in Figure 2. The RIAM method offers a systematic and structured approach to assessing environmental impacts, taking into consideration the specific contexts of Poland and Indonesia's landfill management practices. This analysis applies the RIAM method to compare the landfilling practices and their respective impacts in both countries.

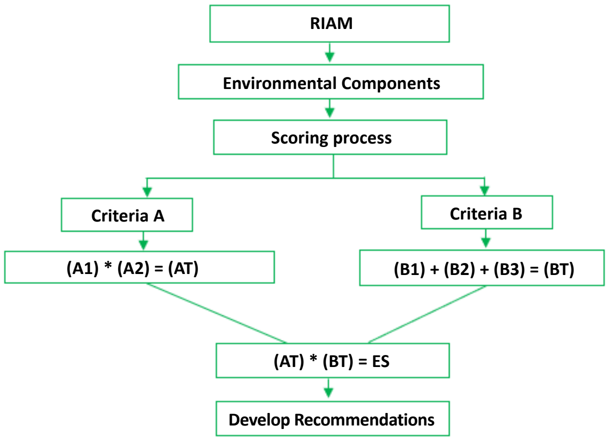

Fig. 2. Flowchart for RIAM matrix work

Source: Resen, Abdul Razzaq and Abbood (2023).

The rapid impact assessment matrix (RIAM) framework systematically classifies environmental components into distinct categories such as leachate, gas emissions and reclamation. Each category is evaluated through specific criteria to ensure a comprehensive assessment. The first criterion, importance (A1), gauges the significance of an issue across local, regional or national scales. Higher importance denotes broader impacts and a greater priority for intervention. The second criterion, magnitude of change/effect (A2), assesses the severity of impacts. This necessitates more substantial interventions for more significant magnitudes. The third criterion, permanence (B1), evaluates whether impacts are temporary or permanent. Permanent impacts require long-term solutions. The fourth criterion, reversibility (B2), considers the ease with which impacts can be reversed. Irreversible impacts are of greater concern. Finally, the fifth criterion, cumulative effect (B3), examines the cumulative nature of impacts. It recognises that cumulative effects can intensify over time and require more strategic planning. Through this detailed and methodical approach, the RIAM framework facilitates informed decision-making and sustainable management of environmental components.

In the context of leachate management, the effectiveness of leachate treatment and its impact on groundwater and surface water quality are of paramount importance. In terms of gas emissions, the extraction and containment of methane, along with the overall impact on air quality, are critical factors to consider. Reclamation efforts focus on the restoration of landfill sites and the development of community spaces, ensuring both environmental recovery and community benefits. This systematic approach ensures that all potential impacts are thoroughly evaluated and addressed, promoting sustainable environmental management. The evaluation of the impacts of each option on environmental components was conducted using the criteria and scales presented in Table 2 (Pastakia & Jensen, 1998).

To utilise the evaluation process, a matrix was created for each option, with components identified and individual criteria scores assigned to each cell. The assessment considered six factors influenced by environmental impact, namely water quality impact, methane extraction, air quality impact, site restoration and community space development. The treatment effectiveness is categorised into three main groups: leachate management, gas emissions and reclamation within the environmental component. During the scoring process, each environmental component received scores for A1, A2, B1, B2 and B3, based on an average of expert opinions regarding the environmental effects of each alternative.

The environmental score (ES) for each component was calculated and then multiplied by the contractual scores detailed in Table 3. The sum of these values was divided by the total number of factors to determine the overall ES for the comparative analysis of landfill practices between Poland and Indonesia. Consequently, the alternative with the least environmental impact was identified and proposed as the best practice for improving waste management in Indonesia.

Table 2. Assessment criteria in RIAM analysis

Criteria	Scale	Description
A1: importance of condition	4	important to national/international interests
	3	important to regional/national interests
	2	important to areas immediately outside the local condition
	1	important only to the local condition
	0	no importance
A2: magnitude of change/effect	+3	major positive benefit
	+2	significant improvement in status quo
	+1	improvement in status quo
	0	no change/status quo
	−1	negative change in status quo
	−2	significant negative disbenefit or change
	−3	major disbenefit or change
B1: permanence	1	no change/not applicable
	2	temporary
	3	permanent
B2: reversibility	1	no change/not applicable
	2	reversible
	3	irreversible
B3: cumulative	1	no change/not applicable
	2	non-cumulative/single
	3	cumulative/synergistic

Source: own work.

Table 3. The range bands of environmental scores in RIAM analysis

Environmental score	Range band	Contractual score	Extent of the environmental impact
From +72 to +108	+E	5	major positive change/impacts
From +36 to +71	+D	4	significant positive change/impacts
From +19 to +35	+C	3	moderately positive change/impacts
From +10 to +18	+B	2	positive change/impacts
From +1 to +9	+A	1	slightly positive change/impacts
0	N	0	no change/status quo/not applicable
From –1 to –9	−A	–1	slightly negative change/impact
From –10 to –18	−B	–2	negative change/impacts
From –19 to –35	−C	–3	moderately negative change/impacts
From –36 to –71	−D	–4	significant negative change/impacts
From –72 to –108	−E	–5	major negative change/impacts

Source: Valizadeh and Hakimian (2019).

RESULTS AND DISCUSSION

This research uses three environmental component variables to analyse the conditions of landfill practices in Poland and Indonesia. Next, each component is evaluated using certain criteria to determine its impact on the landfill site. The assessment scores use RIAM analysis for environmental components: leachate management, gas emissions and reclamation of landfill practices in Poland and Indonesia.

The condition of environmental components in Poland, based on criteria scores (A1, A2, B1, B2 and B3), has a significant impact on landfill management (Table 4). In Poland, the components of leachate management, in terms of water quality impacts, gas emissions for methane extraction and site relocation reclamation, have significance for national or international interests (A1) with the highest degree (4) on the scale. Meanwhile, in terms of the magnitude of the change (A2), it has a positive benefit with a degree of 3 for all environmental components except for the impact of air quality in controlling gas emissions, which requires improvements to the status quo with a degree (2). Likewise, permanent (B1) and unchangeable (B2) indicators have the same degree (3) for both criteria, apart from being cumulative (B3) with degree (2).

Table 4. Results of the matrix components within the Radiowo landfill site located in Poland

Environmental component	Criteria	A1	A2	B1	B2	B3	Score
Leachate management	treatment effectiveness	3	3	3	3	2	72
	water quality impact	4	3	3	3	2	96
Gas emissions	methane extraction	4	3	3	3	2	96
	air quality impact	4	2	3	3	2	64
Reclamation	site restoration	4	3	3	3	2	96
	community space development	3	3	3	3	2	72

Source: own work.

Overall, the risk assessment scores for Poland's landfill practices show strong performance in every environmental component (Fig. 3). The first component is leachate management, which includes treatment effectiveness and water quality impact. Based on the total criteria scores (A1, A2, B1, B2 and B3), water quality impact has a higher score of 96 compared to treatment effectiveness. Similarly, the gas emissions component is highly effective, with methane extraction scoring 96 compared to air quality impact. These indicate that Poland's landfill has robust methane management practices. The last component is reclamation, which also shows high efficacy, particularly in site restoration with a score of 96, reflecting the success of the restoration initiative.

The environmental impact assessment score of Kebon Kongok landfill in Indonesia shows a negative score on the magnitude of change (A2) for all criteria (Table 5). These consistent negative assessments underscore the severity of the environmental challenges associated with landfill operations. Meanwhile, Indonesia received the highest score on the indicators of permanence (B1) and reversibility (B2), with a score of three among all indicators. Overall, the results of this research underscore the need for immediate and effective environmental management practices to address the significant negative and detrimental impacts of the Kebun Kongok landfill.

The RIAM's analysis scores for Indonesian landfills show different results compared to Poland in managing environmental components (Fig. 4). The results indicate that Indonesia faces significant challenges, particularly in leachate management, where treatment effectiveness and impact on water quality received negative scores of –24 and –48, respectively. Likewise, gas emissions management in Indonesia has a negative score for both methane extraction and air quality criteria. Meanwhile, in the reclamation component, Indonesia received a positive score of 24 for site restoration but obtained a negative score for community space development.

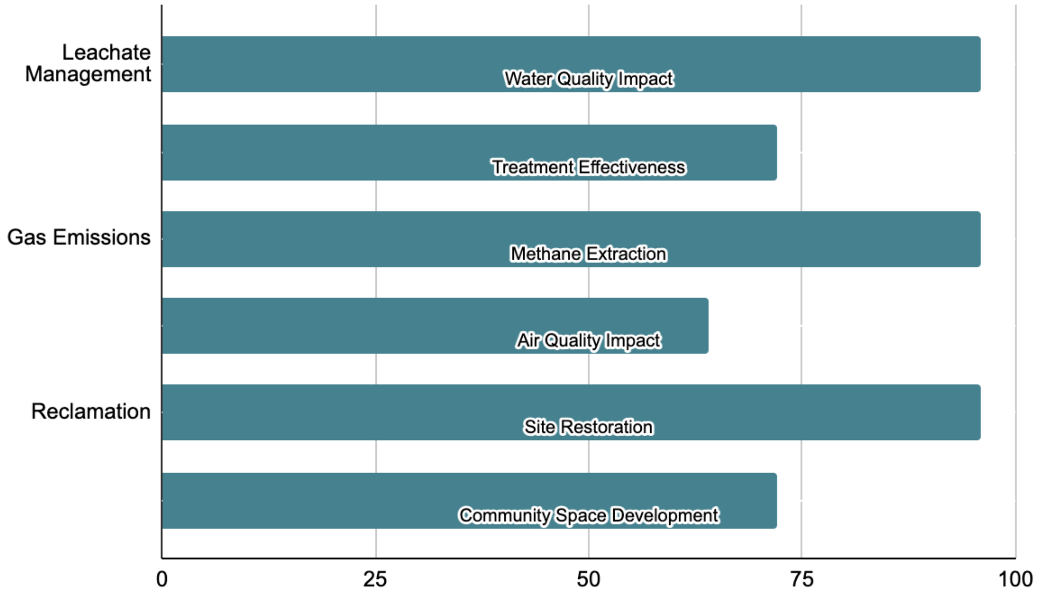

Fig. 3. Poland's total environmental component score based on criteria

Source: own work.

Table 5. Results of the matrix components within the Kebon Kongok landfill site located in Indonesia

Environmental component	Criteria	A1	A2	B1	B2	B3	Score
Leachate management	treatment effectiveness	3	–1	3	3	2	–24
	water quality impact	2	–3	3	3	2	–48
Gas emissions	methane extraction	2	–2	3	3	2	–32
	air quality impact	2	–3	3	3	2	–48
Reclamation	site restoration	3	1	3	3	2	24
	community space development	3	–2	3	3	2	–48

Source: own work.

The average environmental impact of the Radiowo landfill on leachate management and water quality has a significant positive effect, scoring 5 on the contract scale. It falls within the +E band range, with environmental scores (ES) of 72 and 96, respectively. However, efforts to control gas emissions and improve air quality need to be increased, as indicated by an ES of 64, placing it in the +D category. Additionally, the Radiowo landfill scores 96 and 72 on the ES scale for reclamation efforts at relocation sites and community space development areas, respectively, falling within the E band range (Table 6).

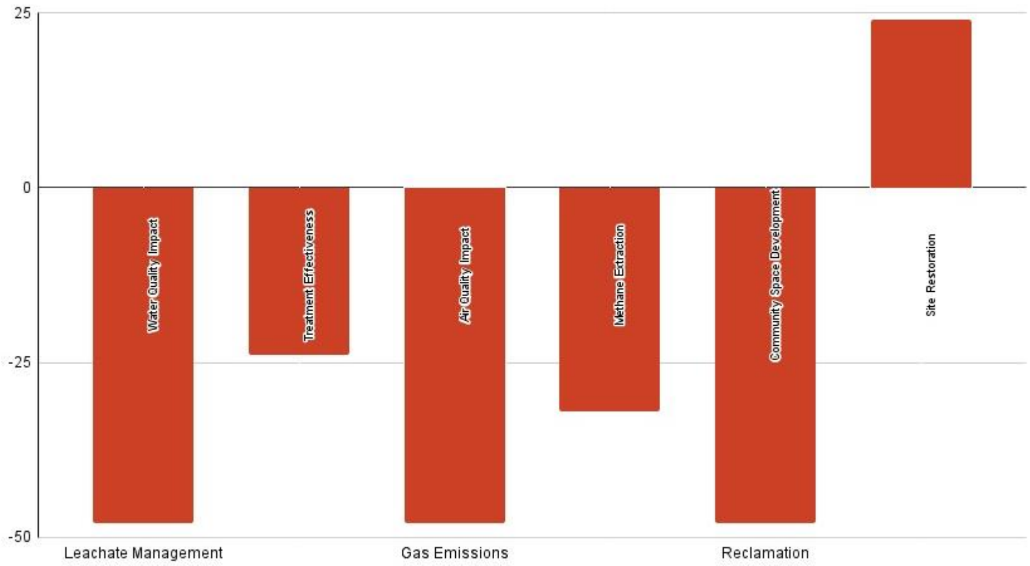

Fig. 4. Total score of Indonesian environmental component score based on criteria

Source: own work.

Table 6. Description of the extent of the environmental impact at the Radiowo landfill in Poland

Environmental component	Criteria	ES	Range bands	Contractual scores	Extent of the environmental impact
Leachate management	treatment effectiveness	72	+E	5	major positive change/impacts
	water quality impact	96	+E	5	major positive change/impacts
Gas emissions	methane extraction	96	+E	5	major positive change/impacts
	air quality impact	64	+D	4	significant positive change/impacts
Reclamation	site restoration	96	+E	5	major positive change/impacts
	community space development	72	+E	5	major positive change/impacts

Source: own work.

In contrast to the Radiowo landfill in Poland, the environmental impact analysis at the Kebon Kongok landfill in Indonesia revealed several concerns regarding various environmental aspects. In terms of leachate management, treatment effectiveness shows a significant negative impact with an ES score of –24 (–C band range), indicating a serious negative impact on water quality. Similarly, the indicators for gas emissions and methane extraction, as well as air quality, fall into the –C and –D categories respectively. In the reclamation component, site restoration is the only area that shows positive results, indicating a moderate positive impact with a score of 24 (+C), signifying success in site restoration. However, community space development received a significantly negative rating, with a score of –48 (–D), highlighting major weaknesses in creating useful community spaces (Table 7).

Table 7. Description of the extent of the environmental impact at the Kebon Kongok landfill in Indonesia

Environmental component	Criteria	ES	Range bands	Contractual scores	Extent of the environmental impact
Leachate management	treatment effectiveness	–24 72	–C	–3	moderately negative change/impacts
	water quality impact	–48 96	−D	–4	significant negative change/impacts
Gas emissions	methane extraction	–32 96	–C	–3	moderately negative change/impacts
	air quality impact	–48 64	−D	–4	significant negative change/impacts
Reclamation	site restoration	24 96	+C	3	moderately positive change/impacts
	community space development	–48 72	−D	–4	significant negative change/impacts

Source: own work.

The comparison (Fig. 5) shows the ES scores between the Radiowo landfill and Kebun Kongok landfill. Based on this, an analysis of the environmental impacts of waste disposal in Indonesia and Poland shows striking differences in environmental management practices and results at the two waste disposal sites. In contrast, Indonesia's landfills face major environmental challenges, with the majority of their negative impacts indicating an urgent need to improve management practices and interventions to mitigate their adverse effects.

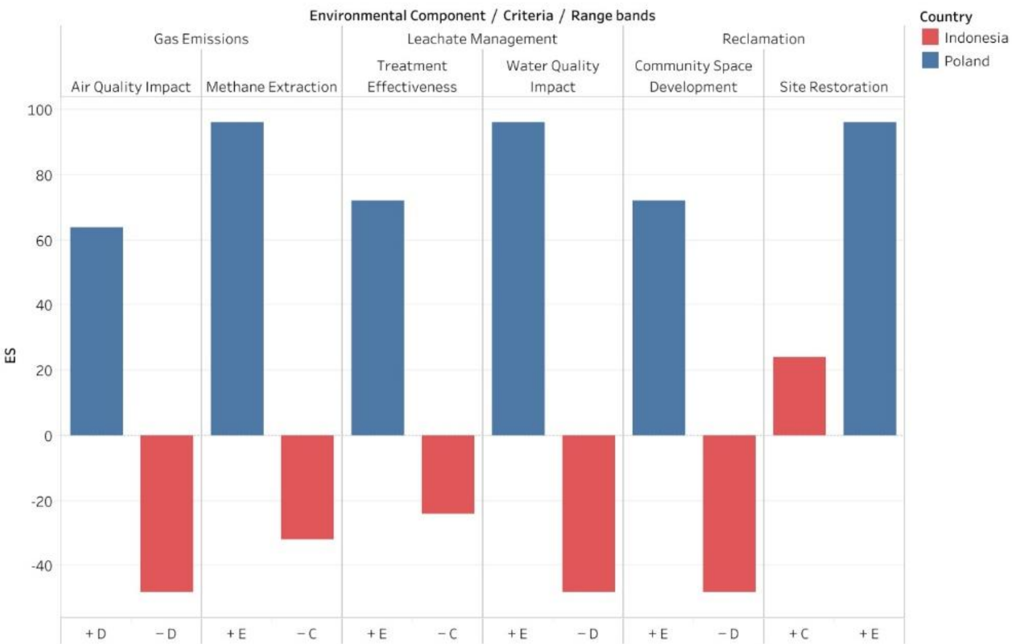

Fig. 5. Environmental impact at Kebon Kongok landfill and Radiowo landfill

Source: own work.

Overall, this comparison highlights that landfill management practices in Poland are much more effective and environmentally friendly, resulting in a significantly positive impact on all assessed components. In terms of gas emissions, Poland scored 96 in managing methane extraction, which affects air quality. They achieve this through a combination of boiler-assisted suction to overcome pipe congestion with real-time infrared analyser monitoring and precise sample quantification of methane emissions. This approach provides crucial data on biogas composition. Additionally, the Radiowo landfill incorporates a natural sealing mechanism that involves insulating materials and integrates a layer of high-density polyethylene (HDPE) foil for enhanced containment. Gas extraction is ingeniously achieved through a passive vertical healthy system that is meticulously designed to effectively capture methane emissions. Vertical collection wells, which are a prevalent and efficient technology for capturing landfill gas (LFG) generated through waste decomposition, enable a comprehensive assessment of the distinct concentration levels of individual biogas components from each well (Kim, Yoshida, Matsuto, Tojo & Matsuo, 2009; Wang & Achari, 2012; Zheng, Rowe & Feng, 2018). Conversely, Indonesia's approach to methane gas capture exhibits dual-pipeline systems by placing vertical and horizontal pipelines within landfill infrastructures. However, these systems are prone to landfill fire accidents (Wahyono, 2015; Ikbal, 2020).

In contrast, Indonesia scored the lowest in leachate treatment (–24) since the Kebon Kongok landfill causes a series of pond constructions in a tiered system. There are three ponds: anaerobic ponds, facultative ponds and maturation ponds, including monitoring wells to access the potential leachate contamination to groundwater. Besides, the drawback of the pond system is that it is prone to leaks due to cracks in the dividing walls. In fact, improper leachate management can significantly threaten groundwater and surface water quality, as the liquid forms when water percolates through the waste, posing a severe risk to groundwater and nearby water bodies (Vaverková, 2019). Additionally, Indonesia is a tropical country where the rainy season lasts about six months from October to March, which translates into a high potential to produce high amounts of methane and leachate during this period. Although the dry season is expected during this time, different regions in Indonesia may experience rainy seasons in months outside of the mentioned period. The country's average humidity remains high even in the dry season. As a result, leachate and gas are continually produced from landfills throughout the year (Emalya et al., 2020).

Compared to Indonesia, Poland scored 96 and 72 in water quality impact and treatment of the leachate, respectively. The Radiowo landfill implements a carefully designed leachate management system that resembles a multi-stage "hydraulic symphony" and a complex network of reservoirs that regulate water movement, ensuring optimal recirculation within the landfill ecosystem. Trench linings and reservoirs are created to protect the flow of leachate water. Here, four leachate purification actions – geochemical, biochemical, physical and biophysical – are carefully regulated. Absorption, ion exchange, dilution and biochemical reactions take centre stage, culminating in a significant improvement in leachate quality. In particular, mechanical filtration in the aeration and saturation zone is vital in improving water quality by removing larger particles. Moreover, Poland has also implemented a sophisticated drainage system with finger drains, retention reservoirs and dedicated circulation networks for rainwater to manage leachate and gas impact on the environment.

The only environmental component in which the Kebon Kongok landfill in Indonesia scored above minus (48) was on-site restoration. This is because they have implemented a multi-stage process for reclaiming the landfill. This process includes conducting waste management and compaction with layers that are each 60-centimetre thick, resulting in a total compacted depth of 2.4 m. They also daily backfill soil with a thickness of 15 cm to form a single "cell". After three months, the daily cover thickness is adjusted to 60 cm with the goal of achieving an annual accumulation rate of 2.4 m. On the other hand, the Radiowo landfill in Poland scored (96) in land restoration. This is due to extensive remedial projects that have been implemented. These projects include slope stability and environmental protection measures such as meticulous landfill contour design, the construction of protective berms and vertical bentonite barriers, the implementation of an active degassing strategy, the establishment of technical highways for efficient access and monitoring and the use of a mineral cover system. Additionally, a biological slope reclamation project utilising compost was also undertaken.

CONCLUSIONS

The comparative analysis of landfill practices in Poland and Indonesia, represented by the Radiowo landfill in Poland and the Kebon Kongok landfill in Indonesia, exhibits significant geographical and operational distinctions. While the Radiowo landfill is located near urban areas and environmentally protected zones and employs a sanitary landfill approach, the Kebon Kongok landfill operates in a rural setting and faces challenges associated with open dumping. This research, employing three key environmental component variables – leachate management, gas emissions and reclamation – highlights significant discrepancies in their respective environmental outcomes.

Utilising the Rapid Impact Assessment Matrix (RIAM), this research provides a thorough evaluation of each component's impact on landfill sites in both countries, presenting a clear contrast in their environmental management effectiveness. The comparative study of landfill practices between Poland and Indonesia elucidates significant disparities in environmental management and impacts, highlighting the efficacy of Poland's strategies and the challenges encountered by Indonesia.

In Poland, the evaluation scores indicate a highly effective landfill management system. Specifically, the components of leachate management are water quality impact (96), gas emissions control with methane extraction (96) and site reclamation in site restoration (96). Poland's advanced leachate treatment technologies, including a multi-stage purification process and sophisticated drainage systems, ensure high water quality and effective leachate containment. Additionally, Poland's methane extraction methods, which integrate real-time monitoring and advanced containment strategies, demonstrate a strong commitment to mitigating greenhouse gas emissions. The country's reclamation efforts further underscore its environmental stewardship, with successful site restoration projects reflecting high efficacy and positive environmental impacts. These results reflect Poland's commitment to sustainable landfill management, which not only mitigates negative environmental consequences but also enhances overall ecological health, establishing a benchmark for effective landfill operations on a global scale.

In contrast, the landfill practices in Indonesia, as exemplified by the Kebon Kongok landfill, reveal substantial environmental challenges. The RIAM analysis scores for Indonesia indicate negative impacts across several criteria. The adverse impacts on treatment effectiveness (–24) and water quality (–48) signify severe inefficiencies and detrimental environmental effects. Furthermore, the poor management of methane extraction (–32) and air quality impact (–48) exacerbate the landfill's environmental issues. Although there is a moderate positive outcome in site restoration (24), the overall negative performance indicates critical deficiencies in Indonesia's landfill management practices, particularly in leachate management and gas emissions control. Indonesia's reliance on a series of pond constructions for leachate treatment, which are prone to leaks and cracks, poses significant risks to groundwater and surface water quality. Furthermore, the dual-pipeline system for methane gas capture in Indonesian landfills is less effective and increases the risk of landfill fires. Despite some positive outcomes in site restoration efforts, the overall environmental impact scores highlight critical deficiencies in Indonesia's landfill management practices.

In conclusion, this research emphasises the critical need to adopt advanced landfill management practices to mitigate environmental impacts. Poland's approach serves as a benchmark for effective landfill management, demonstrating that strategic planning and the integration of advanced technologies can lead to significant environmental benefits. For Indonesia, the findings underscore the necessity of substantial improvements in landfill management practices. By adopting the best practices and technologies demonstrated by Poland, Indonesia can address its environmental challenges and achieve significant improvements in landfill management outcomes. This study contributes to the broader discourse on sustainable waste management practices and provides actionable insights for policymakers and environmental managers in both countries.

Authors' contributions

Conceptualisation: Y.R.L. and L.H.; methodology: Y.R.L. and R.K.; validation: M.G.; formal analysis: Y.R.L. and L.H.; investigation and resources: M.G.; data curation: Y.R.L.; writing – original draft preparation: Y.R.L.; writing – review and editing: Y.R.L. and L.H.

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ANALIZA PORÓWNAWCZA PRAKTYKI SKŁADOWANIA ODPADÓW W POLSCE I INDONEZJI

STRESZCZENIE

Badania opisane w artykule dotyczą globalnego wyzwania, którym jest zarządzanie odpadami. Jego celem były określenie różnic w systemach zarządzania składowiskami oraz analizy głównych wyzwań w implementacji efektywnych systemów zarządzania składowiskami w Polsce i Indonezji poprzez porównanie praktyk zarządzania w obiekcie w Radiowie i na składowisku Kebon Kongok. Dane zostały przeanalizowane z wykorzystaniem *rapid impact assessment matrix* (RIAM). W analizach skupiono się na trzech kluczowych obszarach: zarządzaniu gazami, zarządzaniu odciekami oraz rekultywacji składowisk. Według wyników badań na polskim składowisku bardzo skutecznie zarządza się odciekami z wpływem na jakość wody (96), kontroluje emisjami gazów z ekstrakcją metanu (96) oraz przeprowadza rekultywacje terenu w systemie przywracania terenu do stanu pierwotnego (96). Do tych celów to składowisko wykorzystuje zaawansowane technologie oczyszczania odcieków oraz systemy drenażowe. Praktyki zarządzania indonezyjskiego składowiska, zgodnie z wynikami badań, cechuje poważna nieskuteczność w niemal wszystkich sektorach; najgorszy wynik dotyczył zarządzania odciekami z wpływem na jakość wody (–48), emisji gazów z wpływem na jakość powietrza (–48) oraz rekultywacji terenu w rozwijaniu przestrzeni dla społeczności (–48). Badanie ma wkład w dyskurs na temat zrównoważonego zarządzania odpadami, dostarczając praktycznych wskazówek dla decydentów i menedżerów środowiskowych.

Słowa kluczowe: zarządzanie składowiskiem odpadów, RIAM, zarządzanie gazami, zarządzanie odciekami, rekultywacja