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Methane Emissions from Indonesian Landfills: Site Conditions, Scientific Evidence, and Environmental Risks

Nita Citrasari[1,2*], Indriyani Rachman[1,3], Toru Matsumoto[1]

[1]Graduate School of Environmental Engineering, The University of Kitakyushu, Japan 808-0135

[2]Program Study of Environmental Engineering, Department of Biology,
Faculty of Science and Technology, Universitas Airlangga, Indonesia 60115

[3]Department of Natural Science Education, School of Postgraduate Studies,
Universitas Pakuan, Indonesia 16143

E-mail: nita-c@fst.unair.ac.id; d2dac402@eng.kitakyu-u.ac.jp;
rachmanindriyani@gmail.com; matsumoto-t@kitakyu-u.ac.jp

*Corresponding author details: Nita Citrasari; nita-c@fst.unair.ac.id

ABSTRACT

Methane emissions from municipal solid waste (MSW) landfills are a significant environmental risk, particularly in developing countries like Indonesia. With 63% of MSW composed of biodegradable materials, Indonesian landfills are a major source of methane, a potent greenhouse gas. Despite regulations mandating environmentally sound management, most landfills operate as open dumping (43.1%) or controlled landfills (41.6%), with only 5.3% classified as sanitary landfills. This study aims to assess methane emissions from Indonesian landfills by analyzing site conditions, reviewing scientific evidence, and evaluating associated environmental risks. A national dataset of 341 landfills from 38 provinces and 65 scientific publications were analyzed. Results show that only 15.38% of landfills have gas recovery systems, and literature confirms emissions exceeding 100,000 Mg/year at some sites. Methane-driven fires were reported at 63 sites, with methane identified as the primary cause in 26 cases. This study highlights the urgent need for integrated mitigation strategies, including gas capture, flaring, and waste-to-energy systems, to reduce emissions. Transitioning to sanitary landfill practices with systematic methane management is essential for minimizing environmental risks and supporting Indonesia's climate goals.

Keywords: methane; emission; landfill; Indonesia; environmental risk.

INTRODUCTION

Indonesia, one of the most populous nations globally, faces significant challenges in managing municipal solid waste, with landfilling being the dominant disposal method [1, 2]. Despite national regulations prohibiting open dumping and mandating environmentally sound technologies, such as Law No. 18/2008, Government Regulation No. 81/2012, and Regulation of the Minister of Public Works No. 03/PRT/M/2013 enforcement remains inconsistent, leading to widespread reliance on uncontrolled landfill operations [3–6]. As a result, landfills in Indonesia have become a major source of methane emissions, a potent greenhouse gas with a global warming potential approximately 28 times greater than carbon dioxide over 100 years [7–10].

Methane emissions from the waste sector in Indonesia were estimated at 48.58 million metric tons of CO_2 equivalent in 2022, reflecting a significant increase from previous decades [11]. The primary driver of these emissions is the high organic content of municipal waste, with biodegradable materials such as food waste, paper, and yard waste accounting for over 63% of the total waste stream [7, 12, 13]. When these organic wastes decompose anaerobically in unmanaged landfill environments, they generate substantial quantities of methane [14].

Despite this known risk, the majority of landfills in Indonesia operate as open dumping sites (43.1%) or controlled landfills (41.6%), while only 5.3% meet the criteria for sanitary landfill operations that include leachate control and gas management [6, 12]. This reliance on substandard landfill management practices not only leads to uncontrolled methane release but also increases the risk of landfill fires [15]. Investigated many news reports, and 63 fire incidents over two decades with methane identified as a primary cause in 26 cases.

Previous studies have attempted to quantify methane emissions from Indonesian landfills using various models, including the IPCC, LandGEM, Afvalzorg, and the Thailand Model, with emission estimates varying significantly depending on the method applied [9]. However, these studies have largely focused on individual sites or small regions, leaving a critical gap in understanding methane emissions from a national perspective.

This study aims to provide a comprehensive assessment of methane emissions from Indonesian landfills by analyzing site conditions, reviewing scientific evidence, and evaluating the associated environmental risks. It seeks to identify the gap between emission potential and actual mitigation practices while emphasizing the importance of scalable mitigation strategies, such as gas capture, flaring, and waste-to-energy systems, to support sustainable waste management.

MATERIALS AND METHODS

1. National Analysis of Landfill Conditions

This study used a national landfill dataset from the Indonesian Solid Waste Information System (SIPSN), managed by the Ministry of Environment and Forestry, covering 341 landfills across 38 provinces in 2024 (Figure 1) [12]. Key variables included landfill types (open dumping, controlled, sanitary), waste composition, disposal practices, covering frequency, and the presence of methane recovery systems. Data were analyzed using Microsoft Excel for descriptive statistics, frequency tabulation, and graphical visualization, providing insights into landfill management patterns and methane mitigation efforts [16–18].

FIGURE 1: Landfill location in Indonesia.

2. Review of Published Methane Emission Estimates

A literature review was conducted to gather methane emission data from Indonesian landfills, covering studies from 2015 to 2025, with regulatory references dating back to 2008, 2012, and 2013 [3, 5, 19]. The databases searched included Scopus, ScienceDirect, Google Scholar, SINTA, Garuda, and university libraries. The review encompassed 100 publications using models such as IPCC, LandGEM, the Thailand Model, and Afvalzorg, as well as direct measurements. Extracted data included landfill location, analysis year, estimation methods, emission values (standardized to Mg/year), and methane management practices. This review provided a comparative perspective on methane emissions across diverse landfill sites.

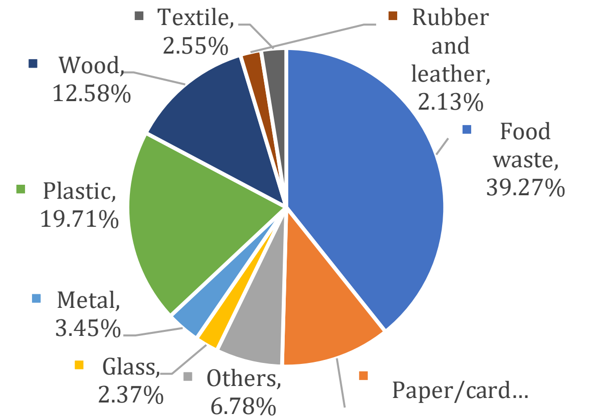
3. Data Analysis

Data analysis compared national landfill conditions with methane emission values from the literature, examining the relationship between landfill types, waste composition, covering frequency, and methane recovery efforts. Descriptive statistics and visual tools (pie charts, bar graphs) highlighted trends, while cross-tabulation identified high-emission sites and assessed mitigation practices. This approach revealed gaps in methane management and emphasized the impact of landfill operations on emission levels [16–18].

NATIONAL ANALYSIS OF LANDFILL CONDITIONS

1. Waste Composition, Methane Potential, and Waste Handling Practices in Indonesia

The national waste composition data show that biodegradable waste dominates municipal solid waste in Indonesia. Based on Figure 2, food waste is the largest component, accounting for 39.27%, followed by wood and branches (12.58%), and paper/cardboard (11.16%) [12]. These three categories alone contribute more than 63% of the waste stream, all of which are major precursors to methane production under anaerobic conditions in landfills. The organic fraction, when unmanaged, becomes the primary contributor to methane generation and subsequent emissions [12, 20].



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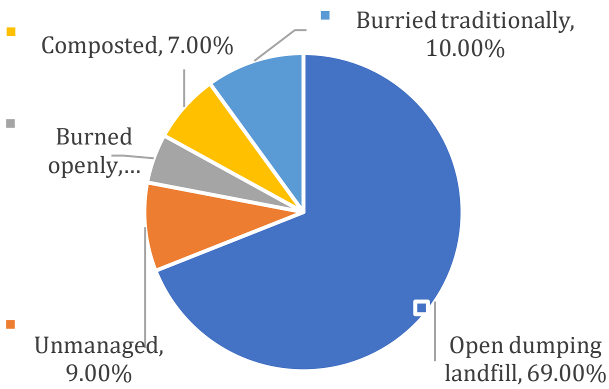


(b)

FIGURE 2: (a) Waste composition (%) in Indonesia, (b) Methods of municipal solid waste management in Indonesia.

Plastics, although non-biodegradable, rank fourth at 18.01% [12]. While plastic itself does not directly decompose into methane, recent studies have suggested that certain types of plastic waste under anaerobic conditions may contribute to methane release during microbial degradation of additives or contamination [21]. This highlights the growing concern about mixed waste degradation in landfills (see Figure 3).

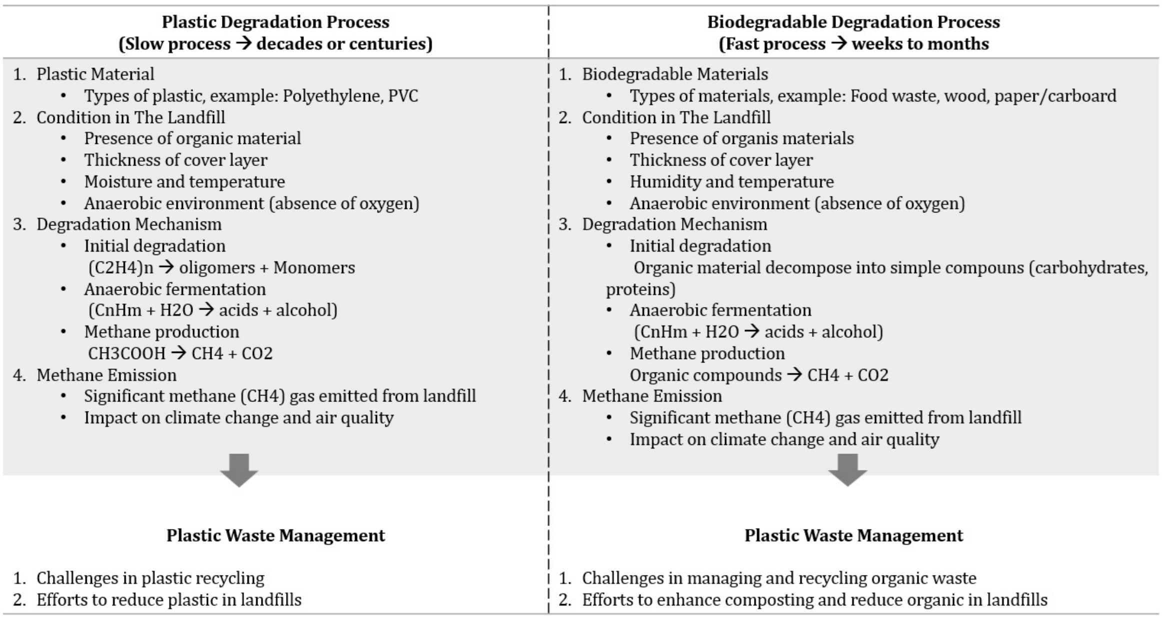


FIGURE 3: Waste Degradation and Its Contribution to Methane Emissions from Landfills.

In terms of waste handling practices (Figure 2), open dumping remains the predominant method, applied in 69% of cases, followed by traditional burial (10%), unmanaged disposal (9%), composting (7%), and open burning (5%) [12]. The heavy reliance on open dumping and unmanaged disposal emphasizes the high vulnerability of Indonesian landfills to methane emissions due to the absence of covering systems, gas capture, and proper waste segregation. Overall, this composition and operational pattern confirm that Indonesian landfills represent a major source of methane potential, especially in the absence of mitigation strategies such as gas recovery or flaring [6, 7].

2. Landfill Operational Systems in Indonesia

An analysis of 341 municipal solid waste landfills across Indonesia reveals a continued reliance on substandard landfill management practices [12]. As shown in Figure 4a, open dumping remains the most prevalent system (147 landfills, 43.1%), followed closely by controlled landfills (142 landfills, 41.6%). In contrast, only 18 landfills (5.3%) meet the criteria for sanitary landfill operations, which typically include infrastructure for leachate control and potential methane gas capture [22]. The operational classification of 34 landfills (10.0%) was not reported, indicating possible data gaps or inconsistencies in reporting [12].

A significant operational issue relates to the proportion of waste directly disposed of in active zones [23]. Figure 4b shows, that 87.4% of landfills dispose of 80–100% of incoming waste without pre-treatment or volume reduction, reinforcing the dominance of full-disposal practices. Only 12.6% implement some level of recovery, such as composting or informal scavenging, though these remain limited and fragmented [12].

The relationship between landfill system type and surface management is further illustrated in Figure 4c, which presents the frequency of covering in active zones across different systems. Open dumping sites are notably associated with the absence of regular covering, with 74 units not applying any surface control at all [12]. Controlled landfills exhibit mixed practices, with most reporting once-a-week or semi-weekly covering. Sanitary landfills show the most consistent routines, with daily or intermediate covering applied to reduce surface exposure and gas release [7, 24, 25].

Finally, Figure 4d highlights the national distribution of covering frequencies. Only 20 landfills (6%) perform daily cover, considered best practice while 86 landfills (25%) apply no cover, increasing the risk of uncontrolled methane emissions [12]. The rest apply covering weekly to yearly intervals or reporting no data. These findings emphasize the critical role of covering practices in determining methane emission potential and underscore the urgent need for policy enforcement and infrastructure improvements to enhance surface management in Indonesian landfills [26, 27].

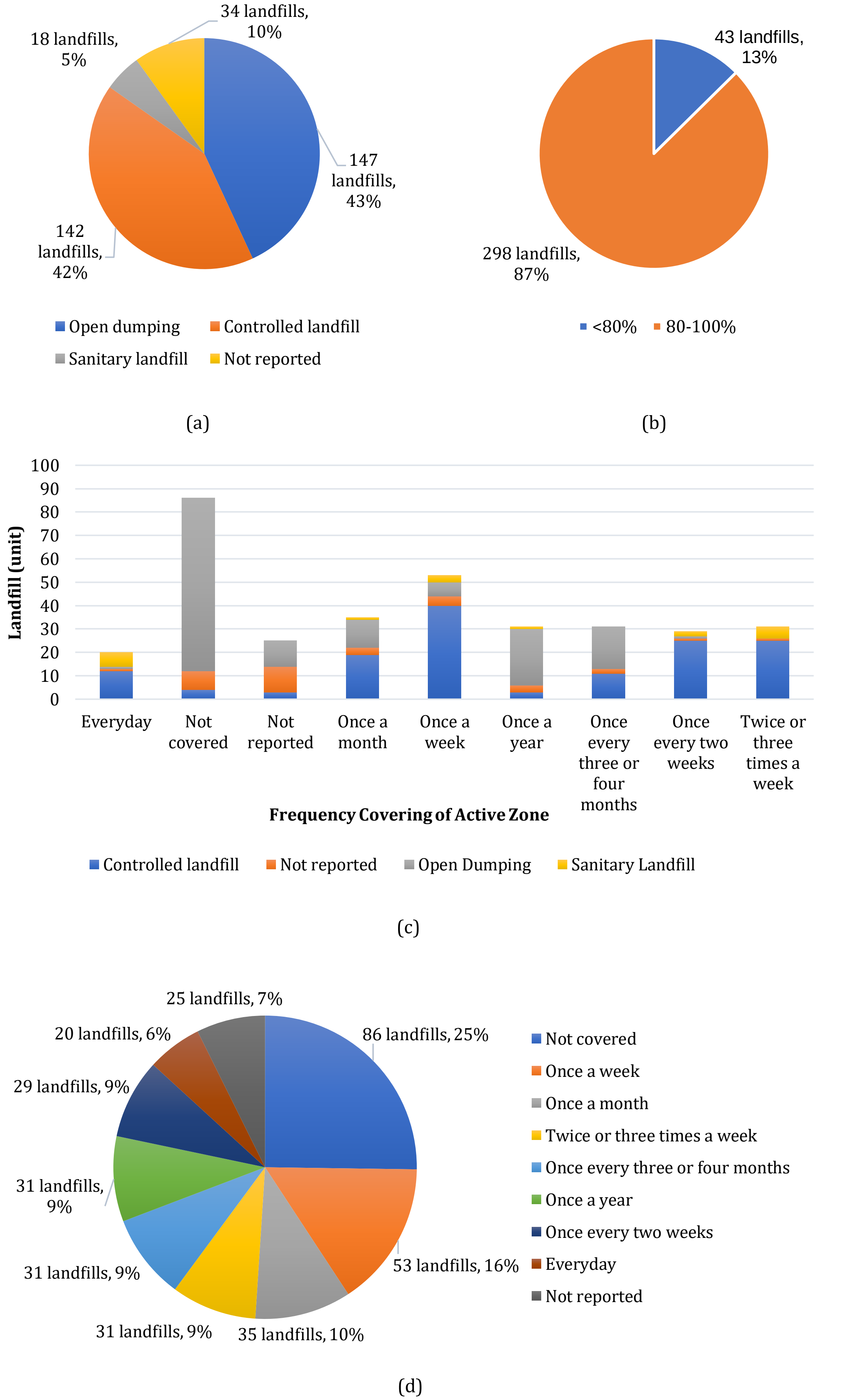


FIGURE 4: Overview of landfill operational practices and active zone management in Indonesia: (a) Distribution of landfill operational systems, (b) Proportion of waste disposed at active zones, (c) Frequency of active zone covering by landfill type, (d) covering frequencies in active landfill zones.

3. Methane-Driven Landfill Fires: A 20-Year Review in Indonesia

Over the past two decades (2005–2025), 63 landfill fire incidents were recorded across 38 landfill sites in Indonesia (see supplementary data). Figure 5 shows methane as the dominant cause (26 cases, 41.27%), with major events including the 2005 Leuwigajah disaster, where a methane explosion triggered a fatal landslide that killed over 140 people, the 2023 Sarimukti fire, and chronic fires at Rawa Kucing Landfill, which burned more than ten times during the review period [28].

These findings indicate that uncontrolled methane emissions are a critical trigger for landfill fires, particularly when combined with poor gas venting and insufficient site management [15, 29]. High temperatures followed as the second most common cause (18 cases, 28.57%), while other contributing factors included dry conditions and burning/human activities (each 5 cases, 7.94%), strong wind (3 cases, 4.76%), and unknown causes (6 cases, 9.52%) [30, 31]. The results highlight the urgent need to monitor and reduce methane emissions from landfills, which remain the primary driver of fire risk, especially in unmanaged or aging landfill cells [32].

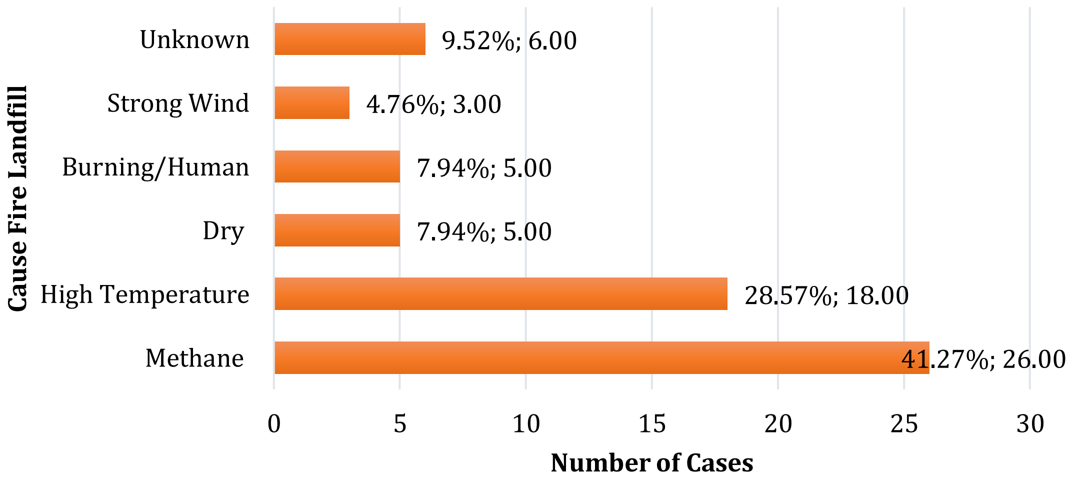
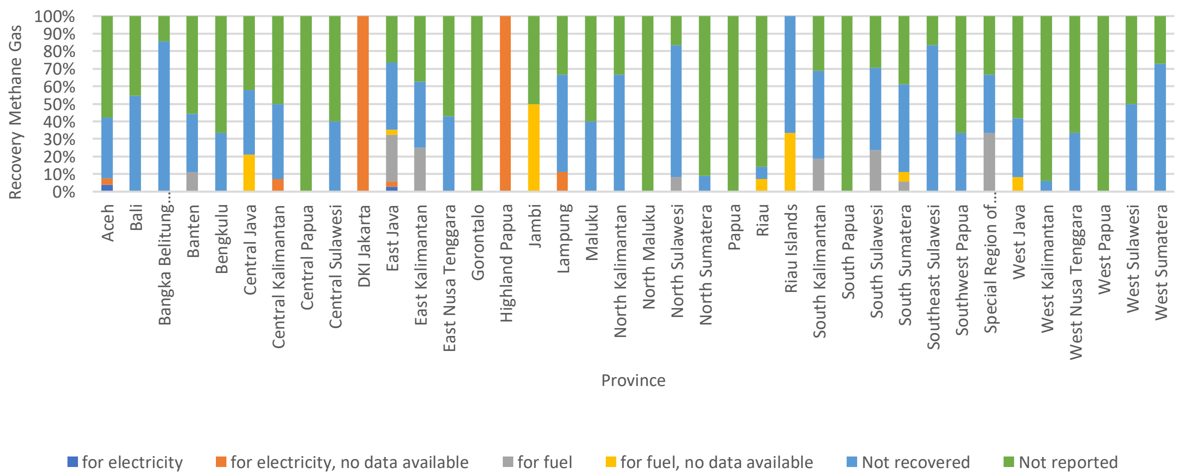


FIGURE 5: Causes of Landfill Fires in Indonesia (2005–2025).

4. Methane Recovery and Utilization in Indonesian Landfills

Figure 6(a) illustrates the status of methane recovery and household utilization across Indonesian provinces. Out of 341 landfills surveyed, recovery practices remain limited and uneven, with most sites categorized as "not recovered" or "not reported." East Java stands out for its relatively advanced efforts, operating nine landfills for fuel, one for electricity, and others under incomplete data categories. East Kalimantan, Aceh, and South Sulawesi also demonstrate early-stage initiatives, though with fewer facilities and inconsistent reporting [12]. These patterns reflect the broader issue of uncontrolled methane emissions from most landfill sites in the country, where capture technologies are not yet widely adopted [33–35].

Only 10 of 38 provinces report providing methane gas for household use, involving a total of 1,217 households (Figure 6b). East Java (477 units), East Kalimantan (382), and Aceh (210) lead in distribution, while provinces such as Banten, South Sulawesi, Yogyakarta, and Southeast Sulawesi show smaller-scale applications. In the remaining 28 provinces, this practice is absent [12]. Although modest in scale, household-level utilization serves as a practical mitigation strategy to reduce methane emissions, particularly in regions lacking centralized recovery systems [7, 22, 36].



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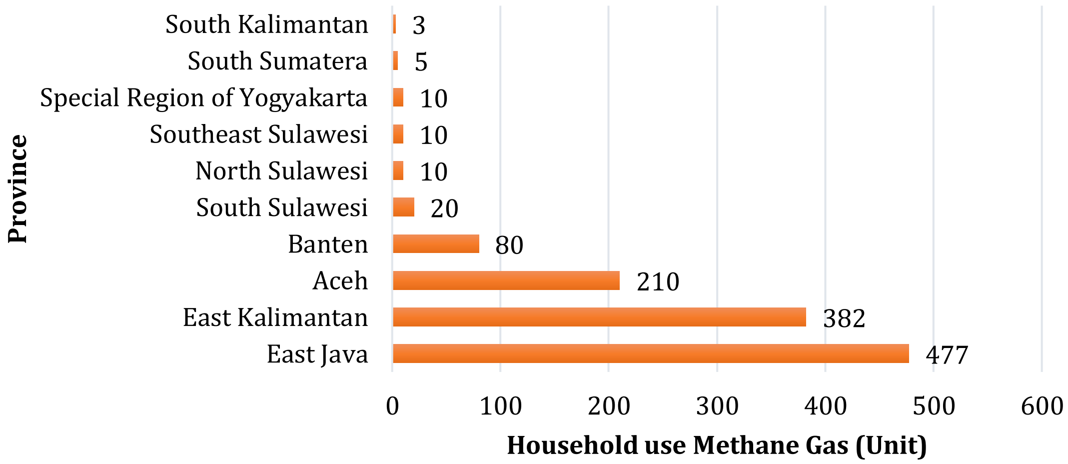


(b)

FIGURE 6: Methane Recovery and Utilization from Landfills in Indonesia by Province: (a) Recovery methods; (b) Households using methane gas from landfills.

5. Literature-Based Methane Emission Estimates from Indonesian Landfills

This section presents supporting evidence from scientific literature to enhance the understanding of methane emissions from Indonesian landfills. A total of 51 methane emission records were compiled, covering 39 unique landfill sites across the country (see, Table 1). These records span different calculation years, including past measurements, current data, and future projections up to the 2030s, offering both historical insights and future estimates.

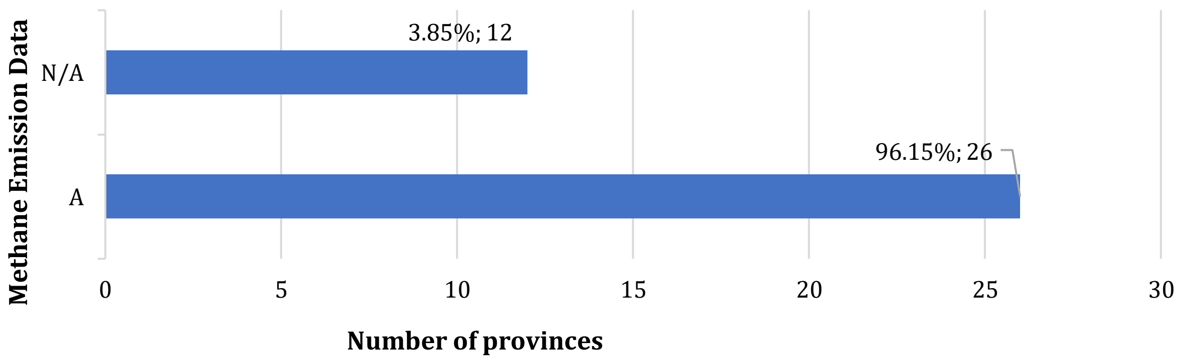
The studies employed a wide range of methodologies, including IPCC (Tier 1 and Tier 2), LandGEM (U.S. EPA model), dynamic system modeling, GasSIM, and direct field measurements (e.g., closed chambers, surface flux, scanning). This variation in methods led to significant differences in estimated emissions. For example, at the Ngipik Landfill, the estimated methane emission for 2023 was 3,205 Mg/year using LandGEM, compared to just 3.01 Mg/year using IPCC Tier 1, a difference of more than 1,000 times (Table 1).

Despite the variation in approach, the compiled data consistently confirm that landfills are a potential major source of methane emissions in Indonesia.

Several large sites such as Tamangapa, Antang, Benowo, and Bantar Gebang each have reported emissions exceeding 100,000 Mg/year. Methane emission data were found in 26 provinces, indicating broad spatial coverage. However, the majority of the estimates (96.15%) originate from academic research, while only one (3.85%) is from a government report, reflecting the lack of institutional monitoring mechanisms (Table 1).

Additional analysis shows that out of the 39 landfills, 20 operate as controlled landfills, 14 as open dumping, and only 3 as sanitary landfills, while 2 lack classification data. Methane recovery infrastructure was reported in only 6 landfills, whereas 13 confirmed the absence of recovery units, and 20 did not report this information. In terms of recovery actions, only 10 landfills reported methane recovery efforts, 3 reported no action, and 26 lacked data (Table 1).

These findings highlight the urgent need for standardizing methane emission assessments and institutionalizing recovery and monitoring practices in landfill management. A full summary of the compiled methane emission records, including calculation methods, emission levels, and landfill characteristics, is provided in Figure 7 and Table 1.



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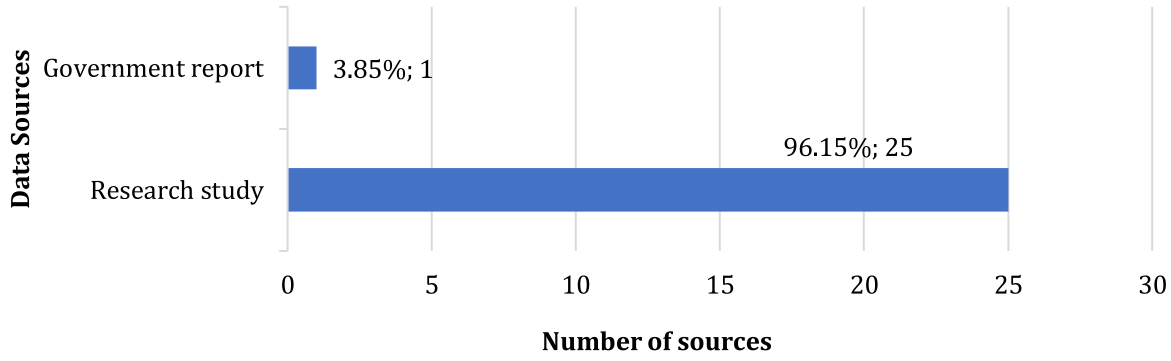

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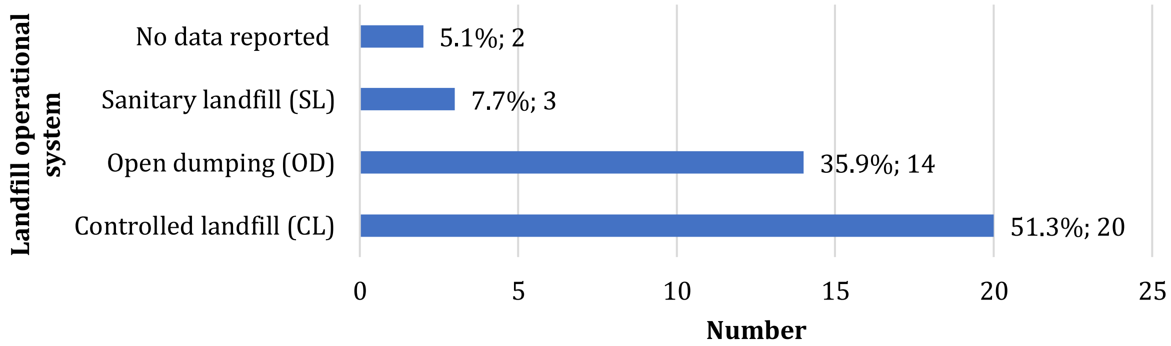

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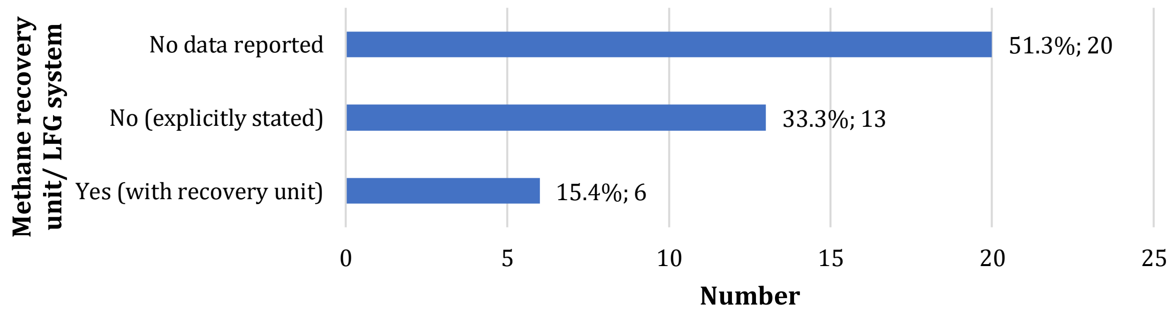

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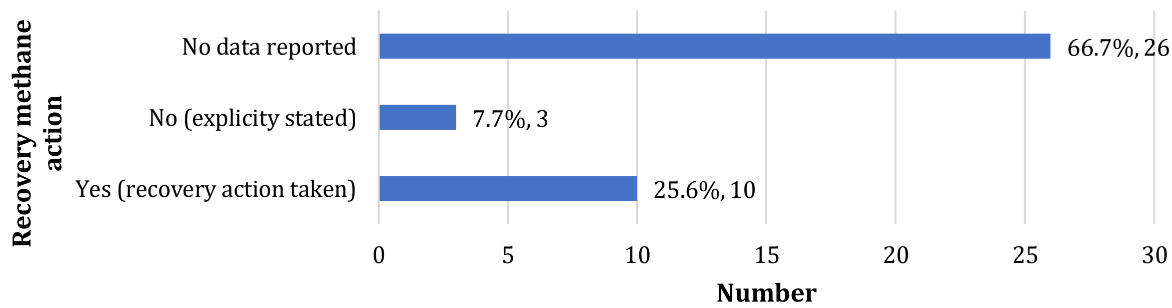

(e)

FIGURE 7: Methane Emission Conditions in Indonesian Landfills Based on Literature Review: (a) Methane emission data; (b) Data source of emission records; (c) Landfill operational systems; (d) Methane recovery unit/LFG; (e) Recovery methane action.

TABLE 1: Summary of Indonesian Landfill Condition (2002–2031).

No.	Landfill	Province/ City	Methane Emission (Mg/year)	Note (s)	Method Calculation	Methane Recovery Unit/ LFG Unit	Recovery Methane Action	Landfill Operational System	Ref.
1.	2 Muara Fajar	Riau/ Pekanbaru	2,744.00	2019	IPCC Tier 2	N/A	N/A	OD	[54]
			34,847.00	2049					
2.	Muara Fajar	Riau/ Pekanbaru	8,280.00		Dynamic system	N/A	N/A	OD	[55]
3.	Tualang	Riau/ Siak	834.80		LandGEM	Yes	Yes	SL	[56]
4.	Kerinci	Jambi/ Kerinci	18.30	2020	IPCC	N/A	N/A	OD	[57]
			779.00	2030					
5.	Talang Tuo	Jambi/ Jambi	8,530.00	2023	LandGEM	Yes	Yes	SL	[58]
6.	Talang Tuo	Jambi/ Jambi	8,002.00		LandGEM	Yes	Yes	SL	[59]
			4.75		Closed chamber, field measurement				
7.	Bakung	Lampung/ Bandar Lampung	2,820.00	2018-2032	IPCC	N/A	N/A	CL	[60]
8.	Kebon Kongok	West Nusa Tenggara	3,234.41		LandGEM	N/A	N/A	OD	[61]
9.	Sarbagita Suwung	Bali/Suwung-Denpasar	2,957.10		IPCC	N/A	N/A	OD	[62]
10.	Sarbagita, Suwung	Bali/Suwung-Denpasar	3,535.06		IPCC	N/A	N/A	CL	[63]
11.	Sarbagita, Suwung	Bali/Suwung-Denpasar	8.74	Before pandemic	IPCC	N/A	N/A	CL	[64]
			2.98	During pandemic					
12.	Bengkala	Bali/ Buleleng	3,800.00		LandGEM default CAA-Conventional scenario	N/A	Yes	SL	[65]
			1,930.00		LandGEM-Inventory scenario				
			990.00		IPCC				
13.	Sarimukti	West Java/ Bandung	2655.02-2730.26		IPCC	N/A	N/A	SL	[66]
14.	Sarimukti	West Java/ Bandung	13,592.58	2024	LandGEM	N/A	No	OD	[2]
			8,661.18	2024	IPCC				
			14,810.41	2025	LandGEM				
			11,462.66	2025	IPCC				
15.	Bagendung	Banten/Cilegon	783.16	2025	LandGEM	Yes	Yes	CL	[67]
16.	Piyungan	Special Region of Yogyakarta/Bantul	544.05	2021	IPCC	N/A	N/A	OD	[68]
			573.85	2025					
17.	Piyungan	Special Region of Yogyakarta/Bantul	4,230.00	2025	LandGEM	N/A	N/A	OD	[69]
			3,463.00	2030					

No.	Landfill	Province/ City	Methane Emission (Mg/year)	Note (s)	Method Calculation	Methane Recovery Unit/ LFG Unit	Recovery Methane Action	Landfill Operational System	Ref.
18.	Jatibarang	Central Java/Semarang	29,961.00	2055	LandGEM	Yes	Yes	CL	[70–73]
			3,892.86		IPCC				
19.	Jeruklegi	Central Java/Cilacap	3,304.00		IPCC	N/A	N/A	CL	[74]
20.	Selopuro	East Java/Ngawi	295.32	Before management	IPCC	Yes	Yes	CL	[75]
			261.48	After management					
21.	Klotok	East Java/Kediri	2,246.32	2032	IPCC	No	No	OD	[1]
22.	Benowo	East Java/Surabaya	15,015.84	2025	IPCC	Yes	Yes	CL	[76, 77]
			15,541.08	2030					
			18,750.00	2025	LandGEM				
			22,670.00	2030					
23.	Benowo	East Java/Surabaya	11,101.52	2025	IPCC	N/A	N/A	CL	[78]
			11,380.45						
24.	Benowo	East Java/Surabaya	180,047.00		IPCC	N/A	N/A	CL	[79]
			100,166.00		Triangular Method				
25.	Randegan	East Java/Mojokerto	1,350.00	household waste	IPCC Tier 2	N/A	N/A	CL	[80]
			264.00	similar to household waste					
26.	Winongo	East Java/Madiun	6,278.00	2015-2025	IPCC	N/A	N/A	CL	[81]
27.	Lempeni	East Java/Lumajang	10,228.00	2025	LandGEM	N/A	N/A	CL	[82]
			2,131	2025	GasSIM				
28.	Gunung Panggung	East Java/Tuban	1,471.00		IPCC	N/A	N/A	CL	[83]
29.	Bestari	East Java/Probolinggo	0.21	2025	IPCC	N/A	N/A	CL	[84]
			0.11	2030					
			0.85	2025	LandGEM				
			0.60	2030					
30.	Ngipik	East Java/Gresik	3,205.00	2023	LandGEM	N/A	N/A	OD	[85]
			3.01		IPCC				
31.	Batu Layang	West Kalimantan/Pontianak	4,298.95		IPCC	N/A	N/A	OD	[86]
32.	Gunung Kupang	South Kalimantan/Banjarbaru	1,490.00	2014-2020	IPCC	N/A	N/A	OD	[87]
			528.00	2021-2024					
33.	Gunung Kupang	South Kalimantan/Banjarbaru	50,470.00		IPCC	N/A	N/A	CL	[88]

No.	Landfill	Province/ City	Methane Emission (Mg/year)	Note (s)	Method Calculation	Methane Recovery Unit/ LFG Unit	Recovery Methane Action	Landfill Operational System	Ref.
34.	Telumelito	Gorontalo/Gorontalo	889,000.00	2023	IPCC	N/A	N/A	N/A	[89]
35.	Toisapu	Maluku/Ambon	886.93	2025	IPCC	Yes	Yes	CL	[90]
36.	Makbon	Southwest Papua/Sorong	87.96	2025	LandGEM	Yes	Yes	SL	[91]
			174.12	2030					
37.	N/A	Papua/Jayapura	20,130.00	2020	IPCC	N/A	N/A	OD	[92]
38.	Puuwatu	Southeasth Sulawesi/Kendari	831.00	2011	LandGEM	N/A	N/A	CL	[13]
			14,400.00	2027					
39.	Tondong	South Sulawesi/Sinjai	326.97	2019	IPCC Tier 2	Yes	No	CL	[93]
			370.71	2029					
40.	Antang	South Sulawesi/ Makassar	1,681,850.00	2025	IPCC	N/A	N/A	CL	[76]
			,715,386.00	2030					
			105,900.00	2025	LandGEM				
			123,900.00	2030					
41.	Tamangapa	South Sulawesi/Makassar	2,240,000.00	2016	IPCC	N/A	N/A	CL	[94]
			4,968,000.00	2026					
42.	Tamangapa	South Sulawesi/Makassar	19,640.00	2026	LandGEM	N/A	N/A	OD	[95]
			4,968.00	2026					
43.	Air Dingin	West Sumatera/ Padang	43,280.00	Scenario 1	IPCC	N/A	N/A	OD	[96]
44.	Terjun	North Sumatera/Medan	12,350.75	2019	IPCC	N/A	N/A	OD	[97]
45.	N/A	North Sumatera/Medan	29,873.10		IPCC	N/A	N/A	CL	[10]
	Bantar Gebang	DKI Jakarta/ Adm. of South Jakarta	113,121.94			N/A	N/A	CL	
	Jatibarang	Central Java/ Semarang	81,530.82			N/A	N/A	CL	
	Piyungan	Special Region of Yogyakarta/ Bantul	16,547.04			N/A	N/A	CL	
	Sarbagita Suwung	Bali/Suwung-Denpasar	57,744.13			N/A	N/A	CL	
	N/A	West Kalimantan/Pontianak	28,459.97			N/A	N/A	CL	
	Tamangapa	South Sulawesi/Makassar	102,402.99			N/A	N/A	CL	
	Benowo	East Java/Surabaya	85.92			N/A	N/A	CL	
	Basirih	South Kalimantan/ Banjarmasin	2,927.32		LandGEM	N/A	N/A	CL	
46.	Basirih	South Kalimantan/ Banjarmasin	388.76		IPCC	N/A	N/A	CL	[98]

No.	Landfill	Province	Methane Emission	Unit	Method Analysis	Methane Recovery Unit/LFG Unit	Recovery Methane Action	Landfill Operational System	Reference
1.	Tamangapa	South Sulawesi/ Makassar	38.30	g/m2/d	point, field measurement	N/A	N/A	OD	[94]
			71.20	g/m2/d	scanning, field measurement				
2.	Bantar Gebang	DKI Jakarta/ Adm. of South Jakarta	74.23	g/m2/h	field measurement	N/A	N/A	CL	[10]
	Cipayung	West Java/Depok	53.55	g/m2/h	field measurement	N/A	N/A	CL	
3.	Tamangapa	Sulawesi/ Makassar	53.70	g/m2/h	field measurement	N/A	N/A	CL	[74]
4.	Sukawinatan	South Sumatera/Palembang	600.00	Nm3/h	calculated based on the volume produced of total wells	Yes	Yes	CL	[99]
5.	Telang	South Kalimantan/ Central Hulu Sungai	6.21E+05	2021 (m3/year)	Modified Triangular Method (MTM)	N/A	N/A	CL	[100]
			4.66E+06	2031 (m3/year)					

DISCUSSION

Indonesia's municipal waste contains over 63% biodegradable materials, making landfills a major source of methane [6, 10, 12]. The widespread use of open dumping and limited waste treatment accelerates anaerobic decomposition without control. These conditions emphasize the need for on-site mitigation technologies, including capture systems, flaring, or landfill gas (LFG) units [37–40]. Municipal solid waste landfills are a potential major source of methane emissions in Indonesia, with several large-scale sites, such as Tamangapa, Antang, Benowo, and Bantar Gebang, reporting emissions exceeding 100,000 Mg/year. Despite this, landfills remain underrepresented in Indonesia's national climate agenda, highlighting their underestimated contribution to greenhouse gas emissions. Globally, landfills are significant methane sources, emitting 30–50 Tg of CH_4 annually, with some cities attributing over 50% of their methane emissions to landfills [8, 41, 42].

An analysis of 39 Indonesian landfills reveals a diverse range of operational systems: Controlled Landfill (CL) accounts for 51.28%, Open Dumping (OD) for 35.90%, and Sanitary Landfill (SL) for just 7.69% [12]. Sanitary landfills are the most effective for methane control due to their use of covering and gas capture systems. For example, using daily cover in sanitary landfills can reduce methane emissions by up to 98.10% [26, 27, 43]. Yet, their adoption is minimal, with most landfills operating as controlled or open dumps, where organic waste undergoes unmanaged anaerobic decomposition [44].

The lack of methane recovery infrastructure is a critical issue. Only 15.38% of landfills reported having gas recovery units, while 33.33% explicitly reported having none, and 51.28% provided no information. Among those with gas recovery actions, 25.64% were actively utilizing methane, while 7.69% had no actions, and 66.67% had no data available [12]. This data gap indicates the absence of routine monitoring and a lack of institutionalized methane management.

Furthermore, methane emission data in Indonesia is predominantly sourced from academic research (96.08%), with only 3.92% from official government reports. This imbalance reveals the lack of a standardized national methane inventory. Emission estimates also vary significantly due to diverse methodologies, IPCC (Tier 1 and 2), LandGEM, GasSIM, dynamic modeling, and field measurements resulting in discrepancies. For example, the Ngipik Landfill's methane emissions were estimated at 3,205 Mg/year using LandGEM but only 3.01 Mg/year with IPCC Tier 1, a difference of over 1,000 times (Table 1).

This situation highlights the urgent need for a comprehensive national methane emissions database and an Indonesia-specific model, similar to Thailand's adaptation of LandGEM [45–48]. Such efforts would enable more accurate estimation and inform targeted mitigation policies.

Effective strategies include methane capture, flaring, and waste-to-energy (WtE) systems. Capture systems collect methane through gas wells while flaring burns it to produce carbon dioxide. WtE systems generate electricity or fuel, offering sustainable economic benefits. For example, Deonar Dumpsite in Mumbai achieved sustainability through financial planning and energy sales [20, 26, 27, 49].

Beyond emissions, methane accumulation also contributes to landfill fires. In the past two decades, 63 landfill fire incidents occurred across 38 sites, with methane identified as a primary or supporting cause in 26 cases. The Rawa Kucing Landfill, experiencing over 10 fire events, exemplifies the risk of uncontrolled methane release (see suplementary data). In the United States, landfill fires cause annual losses of $3 million to $8 million, translating to an average of $361 to $964 per incident, highlighting the economic and environmental risks of uncontrolled methane [50].

These findings emphasize the need for an integrated methane mitigation strategy, combining improved technology, consistent monitoring, and targeted policy interventions. Prioritizing the transition to sanitary landfills with LFG systems can significantly reduce emissions while supporting Indonesia's climate goals. Such a strategy requires government support, technical guidance, and financial incentives to ensure widespread adoption and sustainability [22, 38, 48, 51–53].

CONCLUSION

This study confirms that Indonesian municipal solid waste landfills are a significant source of methane emissions, a potent greenhouse gas contributing to climate change, with 63% of waste composed of biodegradable materials. The analysis of 341 landfills shows that the majority operate as open dumping (43.1%) or controlled landfills (41.6%), with only 5.3% classified as sanitary landfills. These conditions, combined with the absence of consistent covering, limited gas recovery (15.38%), and weak monitoring, allow uncontrolled methane release. Over two decades, 63 landfill fire incidents were reported, with methane as a primary cause in 26 cases. Literature-based evidence supports these findings, with some landfills exceeding 100,000 Mg/year in methane emissions. The study highlights the urgent need for integrated mitigation strategies including capture, flaring, and waste-to-energy systems, to reduce methane emissions and support Indonesia's climate goals. Transitioning to sanitary landfill practices with systematic gas management is essential to mitigate environmental risks and align with sustainable development objectives.

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