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Estimation of Methane Emissions using the IPCC FOD Model with Local Parameters and Mitigation Analysis

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Abstract

The increasing generation of urban waste dominated by organic materials has contributed to increased methane emissions. The objectives of this study were to estimate CH_4 emissions, analyze the influence of waste composition, and develop mitigation scenarios based on the IPCC First Order Decay approach with local parameters. The method used was a quantitative descriptive study using the IPCC 2006 FOD model calibrated with waste generation and composition data for 2015–2024, complemented by sensitivity analysis and simulation of landfill gas management scenarios. The results showed that methane emissions increased cumulatively from 1.12 to 5.14 Gg CH_4/year, influenced by the dominance of the organic fraction of 60–65% and anaerobic landfill conditions without a gas capture system. Scenario analysis showed that mitigation strategies such as flaring, waste-to-energy, and bioreactors were able to reduce emissions by more than 60% compared to business-as-usual conditions. In conclusion, methane emissions are strongly influenced by the amount and composition of waste, as well as the effectiveness of landfill management.

Keywords

Greenhouse Gas Emissions, Landfill Methane, Municipal Solid Waste, Waste Composition Analysis.

1. Introduction

Municipal Solid Waste (MSW) generation has increased substantially due to rapid urbanization, population growth, and tourism activities. Globally, more than 2.01 billion tons of MSW are generated annually and are projected to reach 3.40 billion tons by 2050 without effective intervention (Hoornweg & Bhada-Tata, 2012). Organic waste (44%) and plastics (12%) dominate the global waste stream, contributing significantly to Greenhouse Gas (GHG) emissions and marine pollution (Bertolazzi et al., 2024). In Indonesia, MSW generation reached approximately 67.8 million tons in 2023, with organic waste accounting for 59%, followed by plastics (14%), paper (10%), and metals (5%) (Afnan et al., 2025). In Bali, waste generation ranges from 1.0–1.2 kg/capita/day, dominated by organic and plastic fractions, while tourism accelerates plastic leakage into coastal ecosystems, particularly PET, LDPE, and PP polymers. Under anaerobic landfill conditions, organic waste decomposition generates methane (CH_4), making the waste sector responsible for approximately 3–5% of global GHG emissions; each ton of MSW emits around 89.7 kg CO_2-eq, increasing to 506 kg CO_2-eq for organic fractions, with emission levels strongly influenced by waste management technologies (Gunamantha & Sarto, 2012; Gunamantha et al., 2023).

Methane generation in landfills results from anaerobic decomposition processes in which CH_4 interacts with leachate and contributes to atmospheric pollution and groundwater contamination (Ghosh et al., 2023). As a potent short-lived climate pollutant, methane emissions from MSW landfills are commonly estimated using the IPCC First Order Decay (FOD) model because of its simplicity and reliance on historical waste data. However, applying default IPCC parameters without local calibration may create substantial uncertainty. Previous studies in Brazil, Europe, and Asia identified Methane Correction Factor (MCF), Degradable Organic Carbon (DOC), and methane generation potential as critical determinants of model accuracy (Kim & Yi, 2009; Popita et al., 2015; Heyer et al., 2018; Kim et al., 2023). Similar discrepancies were also reported in tropical regions, including Indonesia, where landfill characteristics differ considerably from IPCC default assumptions (Gunamantha & Yuningrat, 2012).

Despite growing global attention, gaps remain in landfill methane management policies and implementation. Only a limited number of countries have comprehensive mitigation frameworks, while landfill emissions are still underestimated in global inventories. In Indonesia, about 60–70% of Municipal Solid Waste (MSW) is disposed of in open or semi-controlled landfills, making the waste sector contribute around 7.7% of national greenhouse gas emissions, mainly methane. At the local level, Bali experiences increasing pressure on landfill capacity, particularly at Mandung Landfill in Tabanan, where rising organic waste generation is not supported by adequate infrastructure, including limited gas capture systems and incomplete sanitary landfill practices. These conditions increase the risk of uncontrolled methane emissions and leachate pollution, while the adoption of biogas utilization and Waste-to-Energy (WtE) technologies remains limited (Bößner et al., 2019; Silaen et al., 2020; Huda et al., 2020).

Recent mitigation strategies such as composting, Refuse-Derived Fuel (RDF), landfill mining, and biocover systems have shown significant potential in reducing emissions. Integrated approaches combining RDF and WtE can reduce emissions by more than 50% compared to conventional landfill systems. However, effective mitigation requires accurate emission baselines and localized modeling. In Tabanan Regency, despite increasing waste generation trends, no detailed site-specific GHG inventory exists for Mandung Landfill using the FOD IPCC method. Existing data are limited to aggregate waste statistics without emission quantification, creating a critical evidence gap for policy formulation. Moreover, Indonesia still relies heavily on default IPCC parameters in national inventories, which may not accurately reflect tropical landfill conditions and waste characteristics.

This study addresses these gaps by developing a site-specific methane emission inventory for Mandung Landfill using the IPCC FOD model calibrated with local parameters. It integrates waste composition sensitivity analysis, evaluates mitigation scenarios, and projects future waste generation and emissions based on historical trends. The novelty lies in combining localized emission estimation, sensitivity-based assessment of waste fractions, and scenario-based mitigation evaluation within a single integrated framework for a district-level landfill context in Indonesia. The aim of this study is to estimate CH_4 emissions from Mandung Landfill using a locally calibrated IPCC FOD model, to analyze the influence of waste composition variability on emission outcomes, to evaluate applicable mitigation strategies based on emission modeling results, and to project future waste generation along with associated methane emissions in order to support evidence-based landfill management and low-carbon policy development.

2. Literature Review

2.1. Greenhouse Gases and Global Climate Change

Greenhouse gases (GHGs) are key components of the global climate system that regulate Earth's energy balance by absorbing and re-emitting infrared radiation, leading to the greenhouse effect and global warming. The main GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases, with emissions significantly increasing since the industrial era due to human activities, making climate change a major global challenge (Falup et al., 2014; Shukla et al., 2024). In the waste sector, methane is the most relevant gas because it is primarily produced from anaerobic decomposition of organic waste in landfills and has a much higher global warming potential than CO_2 over a 100-year horizon. Although CO_2 is emitted in larger quantities globally, landfill CO_2 is largely biogenic, while CH_4 dominates climate impact from waste, making it the primary focus of mitigation efforts.

Methane emissions from landfills are influenced by waste composition, particularly the high fraction of biodegradable organic matter, operational conditions, and degradation parameters. Falup et al. (2014) stated that in tropical landfill environments, high temperature and humidity accelerate anaerobic processes, increasing CH_4 generation. Therefore, emission estimation commonly uses the First Order Decay (FOD) model, which provides a standardized and time-dependent approach recommended by IPCC for consistent and comparable inventories (Shukla et al., 2024). Compared to other sectors, such as energy and industry, dominated by CO_2 emissions, the waste sector offers more direct and practical mitigation opportunities through landfill gas capture, flaring, energy recovery, and reduction of organic waste at source. These strategies are more feasible at local levels due to the localized nature of methane emissions. Focusing on methane provides a strategic and practical approach for emission reduction in landfill systems, particularly in developing regions where waste management infrastructure is still limited but mitigation potential is high.

2.2. Greenhouse Gas Emissions Production from Final Processing Sites

A landfill (*Tempat Pembuangan Akhir*/TPA) is a key component of solid waste management systems, serving as the final disposal site for residual waste that cannot be recycled or composted. It functions as an open biological reactor where anaerobic decomposition of organic waste produces greenhouse gas emissions, dominated by methane (CH_4), along with smaller amounts of CO_2 and other compounds. Methane formation occurs through sequential biochemical stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, ultimately producing CH_4 as the main end product (Saltykov & Trifonov, 2023). Due to its high global warming potential, approximately 28–36 times higher than CO_2 over 100 years, methane significantly contributes to climate change, while also posing local environmental risks such as odor, explosion hazards, and air pollution (Elagroudy & Warith, 2009; Listiyani & Yulianto, 2023).

Emission estimation commonly uses models such as LandGEM (US EPA) and IPCC guidelines (Tier 1–3), which account for waste quantity, composition, and degradation parameters. Methane emissions are strongly influenced by high organic content waste, tropical climatic conditions, and landfill operational practices (Christiawan & Pratama, 2019). Mitigation strategies include landfill gas capture, flaring, energy recovery, bioreactor landfill systems, and biorefinery concepts, which improve gas utilization and reduce emissions (Dragicevic, 2009; Bolan et al., 2013). However, implementation in developing regions faces constraints such as limited data availability, high investment costs, and institutional capacity gaps. Effective mitigation also depends on governance, public awareness, and integrated policy support, while life cycle assessment confirms that landfill choice significantly affects total emissions (Caicedo-Concha et al., 2021). TPA Mandung represents a typical developing-region landfill, making it relevant for analyzing methane generation dynamics and informing context-specific mitigation strategies.

2.3. IPCC FOD Method in Landfill Methane Emission Analysis

The First Order Decay (FOD) model is a widely used first-order kinetic approach for simulating the time-dependent degradation of organic matter and is formally adopted by the IPCC as the standard methodology for estimating methane emissions from solid waste disposal sites. In this framework, methane generation is modeled as a function of the remaining degradable organic carbon, allowing a more realistic representation of cumulative and delayed emissions compared to simple mass-balance approaches (Bogner et al., 2008). Its main strength lies in its ability to incorporate temporal dynamics, waste composition variability, and site-specific degradation conditions, making it suitable for application in diverse landfill contexts, including data-limited developing regions.

The model assumes that degradation follows an exponential decay process, where the decay constant (k) controls the rate of organic carbon conversion into methane and is strongly influenced by environmental conditions such as temperature, moisture, and microbial activity. Although FOD improves emission accuracy, it remains sensitive to parameter uncertainty, particularly DOC, MCF, and k, which require local calibration to avoid estimation bias. Empirical studies emphasize that parameter selection critically affects model reliability, and laboratory methods such as BMP tests are often used for validation. While more complex multi-phase models may better capture degradation heterogeneity by Blum et al. (2009), FOD remains the foundational framework in greenhouse gas inventory systems due to its balance of simplicity, adaptability, and consistency. It has also been extended to broader environmental applications, including contaminant transport and reaction network modeling, confirming its versatility as an applied theoretical tool.

2.4. Integration of First Order Decay Theory

In applied theory, GHG mitigation from landfills is understood as a set of technical, biological, and institutional interventions aimed at reducing methane formation, release, or impact from anaerobic decomposition of organic waste, where methane is the dominant landfill gas with a significantly higher global warming potential than carbon dioxide (Kiehbadroudinezhad et al., 2024). The most established approach is Landfill Gas (LFG) capture and utilization, which diverts methane from direct atmospheric emission into energy recovery systems, such as

Landfill Gas-To-Energy (LFGTE), thereby simultaneously reducing emissions and generating renewable energy (North, 2016). Bayles (2013) stated that advanced systems such as bioreactor landfills further enhance mitigation by accelerating controlled decomposition through moisture optimization, increasing methane production predictability, and improving gas recovery efficiency.

Biological mitigation strategies, including biofilters and methane-oxidizing cover soils, reduce emissions by converting methane into CO_2 and water before release (Park et al., 2010; Abushammala et al., 2014). Semi-aerobic landfill and phytocapping approaches further reduce methane formation by enhancing oxygen availability and promoting oxidation processes. Upstream waste diversion through source separation, composting, and anaerobic digestion reduces organic load entering landfills, directly lowering methane generation potential (Sahu & Reddy, 2024; Rangga et al., 2024). However, North (2016) stated that implementation is constrained by financial, technical, and institutional limitations in developing regions. Policy instruments such as regulation, incentives, and monitoring systems are critical to scaling mitigation effectiveness (Lair et al., 2024). Ultimately, integrated landfill systems are evolving toward biorefinery concepts that combine waste management with energy production and circular economy benefits (Bolan et al., 2013; Kiehbadroudinezhad et al., 2024).

3. Methods

This study used a quantitative descriptive design to estimate methane (CH_4) emissions from Mandung Landfill, Tabanan Regency, using the IPCC First Order Decay (FOD) model. It did not examine causal relationships but focused on quantifying emissions and assessing mitigation options through deterministic modeling. Methane emissions were the main outcome variable, while waste generation, composition, and projected trends served as analytical inputs. Controlled variables included landfill system boundaries, operational characteristics, and parameters from the IPCC 2006 Guidelines and 2019 Refinement. The study was conducted at Mandung Landfill, Bali, from September–December 2025. The population comprised all Municipal Solid Waste (MSW) disposed of during the operational period, while the analytical unit used annual waste data from 2015 to 2024. Special attention was given to biodegradable fractions such as food waste, garden waste, paper, cardboard, wood, and textiles that significantly contribute to methane formation.

Data collection relied exclusively on secondary quantitative data obtained from official institutional reports and landfill administrative records. The collected information included annual waste generation, waste composition, landfill operational characteristics, and supporting documentation required for methane estimation. To ensure data validity, only verified and officially published datasets were utilized. Conceptual and model validity were established through the application of the internationally recognized IPCC 2006 Guidelines and the 2019 Refinement framework for landfill methane estimation. Model validation was further undertaken by comparing estimated emission values with IPCC default assumptions and findings from previous studies conducted at comparable landfill sites. Reliability was ensured through the consistent application of deterministic mathematical equations and standardized calculation procedures, enabling reproducibility when identical datasets and parameters are employed.

Data analysis employed a quantitative descriptive approach using a spreadsheet-based IPCC First Order Decay (FOD) model to estimate methane (CH_4) emissions from Mandung Landfill during the 2015–2024 period. The analytical procedures began with data preparation and classification of biodegradable waste fractions, followed by the determination of degradation parameters adjusted to local tropical conditions, including Degradable Organic Carbon (DOC), methane generation rate constant (k), and Methane Correction Factor (MCF). These parameters were subsequently incorporated into the FOD model to simulate methane generation resulting from the gradual anaerobic decomposition of waste over time. In addition to estimating annual methane emissions, future waste generation and methane emissions were projected to support long-term emission forecasting under different landfill management conditions.

Sensitivity analysis was conducted to identify waste fractions that most influence methane generation and to assess the responsiveness of emission estimates to changes in key model parameters. Results were presented through numerical trends, tables, graphs, and emission projections without inferential statistical testing, as the study used deterministic mathematical modeling. A quantitative SWOT analysis was applied to determine mitigation priorities by evaluating internal (strengths and weaknesses) and external (opportunities and threats) factors in landfill management and methane reduction. Mitigation options, including landfill gas collection, flaring, Waste-to-Energy (WtE), biomethane recovery, biocover systems, and landfill closure, were compared based on technical feasibility, emission reduction potential, operational constraints, and environmental benefits. Weighted scoring established prioritized strategies, and findings were interpreted in relation to landfill operations, anaerobic degradation theory, and prior studies to support sustainable methane mitigation.

4. Results

4.1. Estimation of Methane Emissions from Mandung Landfill

Mandung Landfill, located in Tabanan Regency, Bali, serves as the primary disposal facility for municipal solid waste in the region and represents a relevant case for methane emission estimation using the IPCC First Order Decay (FOD) model. Operating under tropical wet climate conditions characterized by high rainfall and warm temperatures, the landfill provides favorable conditions for anaerobic decomposition of organic waste and subsequent methane (CH_4) generation. The site has historically relied on open dumping practices and has gradually transitioned toward controlled landfill management, while receiving waste streams dominated by biodegradable fractions, particularly food and garden waste with high methane generation potential. This study utilized secondary data obtained from the Environmental Agency of Tabanan Regency, regional waste management reports, and the National Waste Management Information System (*Sistem Informasi Pengelolaan Sampah Nasional*/SIPSN). The dataset comprised annual records of waste disposed of at Mandung Landfill from 2015 to 2024 and was selected to support the FOD approach, which requires historical waste inputs to simulate progressive organic degradation and methane formation over time. The multi-year dataset further enabled the analysis of temporal trends, improved the stability of methane emission estimates, and facilitated future projections of waste generation and associated emissions.

Table 1. Solid Waste Generation in Tabanan Regency (2015-2024)

Year	Solid Waste Generation (Ton)	Population (Persons)	MSW Generation Rate (Ton/Capita/Year)
2015	79,235.89	435,400	0.182
2016	79,781.84	438,400	0.182
2017	80,309.60	441,300	0.182
2018	80,800.95	444,000	0.182
2019	81,292.31	446,700	0.182
2020	84,247.48	461,600	0.183

Year	Solid Waste Generation (Ton)	Population (Persons)	MSW Generation Rate (Ton/Capita/Year)
2021	84,247.48	465,000	0.181
2022	84,923.09	469,300	0.181
2023	84,922.73	471,335	0.180
2024	86,571.07	467,700.00	0.185

Table 1 shows an overall increase in solid waste generation at Mandung Landfill during 2015–2024, generally associated with population growth and changing consumption patterns. During 2015–2019, waste generation increased relatively steadily with stable per capita waste values, indicating consistent consumption behavior. A sharper increase occurred during the COVID-19 period (2020–2021), likely driven by higher household activity, increased use of food delivery services, and greater consumption of single-use packaging. In the post-pandemic period (2022–2024), waste generation continued to rise, with a notable increase in 2024 despite a slight population decline, suggesting that non-demographic factors such as economic and tourism recovery, higher consumption levels, and improved waste recording systems contributed significantly to the increase in waste generation.

Table 2. Composition of Solid Waste at the Mandung Tabanan Landfill

Year	Food Waste (%)	Wood & Garden Waste (%)	Paper & Cardboard (%)	Plastic (%)	Metal (%)	Textile (%)	Rubber & Leather (%)	Glass (%)	Others (%)
2024	29.20	39.76	2.84	10.51	0.34	2.28	1.94	0.94	12.19
2023	29.21	39.76	2.84	10.51	0.33	2.28	1.94	0.94	12.19
2022	30.00	40.00	3.00	10.00	0.32	2.30	2.00	1.00	11.38
2021	5.00	39.00	37.00	10.00	0.50	1.00	2.00	1.00	4.50
2020	5.00	39.00	37.00	10.00	0.50	1.00	2.00	1.00	4.50
2019	5.00	39.00	37.00	10.00	0.50	1.00	2.00	1.00	4.50
2018	5.00	39.00	37.00	10.00	0.50	1.00	2.00	1.00	4.50
2017	5.00	39.00	37.00	10.00	0.50	1.00	2.00	1.00	4.50
2016	5.00	39.00	37.00	10.00	0.50	1.00	2.00	1.00	4.50
2015	5.00	39.00	37.00	10.00	0.50	1.00	2.00	1.00	4

Table 2 presents the waste composition data used to calculate total Degradable Organic Carbon (DOC), which served as a key input in the IPCC First Order Decay (FOD) model. To address potential variations in waste composition across different years, the study incorporated sensitivity analysis to quantitatively evaluate the effects of changes in composition, DOC, degradation rate (k), and Methane Correction Factor (MCF) on methane emission estimates. Although the use of secondary data may introduce uncertainty through potential underestimation or overestimation of emissions, this approach is consistent with the IPCC 2006 Guidelines and 2019 Refinement, which allow the use of standardized assumptions under limited local data conditions. Therefore, uncertainty in this study was treated not as a methodological limitation, but as a basis for developing adaptive and risk-based methane mitigation strategies.

The FOD model parameters applied in this study indicate that country-specific values of DOC are generally higher than the IPCC default values for several waste fractions, particularly food waste, garden waste, paper, wood, textiles, and industrial waste. This suggests a higher potential for biodegradable organic carbon availability and methane generation under local conditions at Mandung Landfill. The methane generation rate constant (k) was also adjusted to reflect the moist tropical climate of Bali, which accelerates anaerobic decomposition processes. In contrast, several parameters, including DOCf, methane Fraction (F), conversion factor, Oxidation Factor (OX), and delay time, were maintained at IPCC default values to ensure methodological consistency and comparability. The use of localized parameters enhances the representativeness and accuracy of methane emission estimation compared to relying solely on default IPCC assumptions.

The assumptions applied in the model are based on historical waste data from 2015–2024 and representative waste composition data from 2024, in accordance with IPCC guidance for cases with limited annual composition records. Key parameters such as DOC, MCF, and k were adjusted to reflect local landfill conditions and tropical climate characteristics, while methane F and OX were retained as default values. The model assumes the absence of an active landfill gas recovery system, and uncertainty is addressed through sensitivity analysis of key parameters. These assumptions are supported by field conditions indicating that Mandung Landfill operates as a semi-controlled landfill characterized by open dumping practices, limited soil cover, mixed municipal solid waste deposition, leachate accumulation, and no gas capture infrastructure. High rainfall and humidity further justify higher MCF and k values typical of wet tropical environments, while limited cover supports minimal methane oxidation. Collectively, these conditions validate the applicability of the IPCC FOD model and strengthen the reliability of methane emission estimates as a reflection of actual landfill operations.

Table 3. Estimated CH4 Emissions

Year	CH_4 Emissions (Gg)	CH_4 Emissions (tons)	CO_2e Emissions (tons)
2015	0.00	0.00	0.00
2016	1.12	1,115.70	27,892.62
2017	2.00	2,000.85	50,021.33
2018	2.71	2,713.49	67,837.28
2019	3.29	3,294.93	82,373.32
2020	3.78	3,775.60	94,390.07
2021	4.21	4,212.52	105,313.09
2022	4.57	4,573.28	114,332.00

As shown in Table 3, methane emissions from Mandung Landfill estimated using the IPCC FOD model increased cumulatively from 0.00 Gg CH_4 in 2015 to 5.14 Gg CH_4 (5,142.87 tons) in 2024 due to continuous waste accumulation and anaerobic degradation of organic waste. CO_2e emissions also increased from 27,892.62 tons in 2016 to 128,571.80 tons in 2024, indicating a significant contribution of landfill methane to greenhouse gas emissions. The consistent increase reflects the cumulative nature of the FOD model, where emissions are generated not only from newly disposed waste but also from the ongoing decomposition of previously accumulated waste. These findings indicate that, without mitigation measures, future waste accumulation will continue to increase methane emissions at Mandung Landfill.

4.2. Contribution and Sensitivity of Solid Waste Composition

Based on the solid waste composition data used in this study, the solid waste fraction entering the Mandung Landfill is dominated by easily biodegradable organic solid waste, consisting of food scraps and garden waste, followed by paper/cardboard, textiles, wood, and other non-organic fractions. Within the IPCC FOD method framework, each of these fractions has a different DOC value, so their contribution to methane formation also varies.

Variations in solid waste composition indicate significant differences in the proportion of biodegradable materials, which directly influence methane (CH_4) generation potential. Waste compositions with higher shares of food waste and other easily degradable organic fractions tend to produce greater methane emissions, particularly during the early stages of anaerobic decomposition due to their rapid biodegradability. In contrast, compositions with a more balanced mix of organic materials result in a more gradual methane generation pattern over time. Meanwhile, waste streams dominated by paper, cardboard, and garden waste with lower food waste content tend to exhibit slower decomposition rates, leading to reduced short-term methane emissions but potentially more prolonged emission periods due to the slower breakdown of lignocellulosic materials.

Table 4. Comparison of Emission Estimation Results

Year	CH4 Emission			
	Composition 1 (Ton)	**Composition 2 (Ton)**	**Composition 3 (Ton)**	**Composition 4 (Ton)**
2015	0.00	0.00	0.00	0.00
2016	1,115.70	293.95	1,121.51	997.23
2017	2,000.85	556.42	2,009.78	1,857.71
2018	2,713.49	791.60	2,723.89	2,604.90
2019	3,294.93	1,002.98	3,305.81	3,257.18
2020	3,775.60	1,193.68	3,786.39	3,829.77
2021	4,212.52	1,375.50	4,223.11	4,366.05
2022	4,573.28	1,538.70	4,583.42	4,834.49
2023	4,883.25	1,688.09	4,892.89	5,253.65
2024	5,142.87	1,822.84	5,151.98	5,622.13
Total	31,712.51	10,263.77	31,798.79	32,623.10

Table 4 shows that the variations in solid waste composition significantly influence methane emission estimates at Mandung Landfill due to differences in biodegradable organic content and DOC. Compositions dominated by biodegradable fractions such as food waste, wood, branches, and paper generally produce higher methane emissions because of their higher DOC contribution in the IPCC FOD model. Among the scenarios, Composition 4 generated the highest cumulative methane emissions during 2015–2024, followed by Compositions 3 and 1, while Composition 2 produced the lowest emissions despite having the highest food waste proportion. This indicates that methane generation is not solely determined by food waste content but is also strongly affected by the proportion of slowly degradable materials such as wood and paper, which contribute to long-term methane formation.

The sensitivity analysis further confirms that waste fractions such as wood branches and paper have the strongest influence on methane emissions at Mandung Landfill. An increase in wood–branch content from around 10% to approximately 40% leads to a substantial increase in cumulative methane emissions, showing nearly a threefold difference across scenarios. These findings highlight that accurate representation of waste composition is critical in FOD-based modeling and that lignocellulosic waste fractions play a key role in long-term methane generation dynamics. Controlling and managing these biodegradable fractions should be prioritized in landfill methane mitigation strategies.

4.3. Evaluation of Alternative Methane Emission Mitigation Strategies

Methane mitigation strategies in this study were evaluated quantitatively using the IPCC First Order Decay (FOD) model with localized parameters from Mandung Landfill. The evaluation focused on comparing the numerical emission reduction potential of eight scenarios, consisting of S0 (Business as Usual/BAU), S1 (Flare), S2 (Electricity), S3 (Heat), S4 (Renewable Natural Gas/RNG), S5 (Low Flow Gas Recovery), S6 (Landfill Closure), and S7 (Bioreactor Landfill), without detailed financial or social feasibility analysis. Each scenario represented a different landfill gas management approach and was simulated by modifying key methane control parameters, including gas capture targets, ramp-up years, Methane Destruction Efficiency (MDE), utilization efficiency, and oxidation factor changes, to estimate annual methane emission reductions quantitatively.

Table 5. Scenario Simulation Parameters (S0-S7)

Scenario	Capture Target %	Ramp Up Years	MDE %	UtilEff%	Change OX
S0 BAU	0.00	0.00	0.00	0.00	0.00
S1 Flare	0.50	1.00	0.98	0.00	0.00
S2 Electricity	0.60	2.00	0.95	0.90	0.00
S3 Heat	0.60	2.00	0.95	0.90	0.00
S4 RNG	0.85	4.00	0.99	0.95	0.00
S5 LowFlow	0.65	3.00	0.90	0.60	0.00
S6 Closure	0.70	1.00	0.98	0.20	0.10
S7 Bioreactor	0.80	3.00	0.95	0.80	0.00

Table 5 shows the scenario-based parameters used to evaluate methane (CH_4) mitigation potential at Mandung Landfill under different landfill gas management strategies. The baseline scenario (S0) represents a business-as-usual condition with no gas capture or treatment, resulting in uncontrolled methane emissions. Scenario S1 assumes a basic flaring system with moderate capture efficiency and rapid implementation, focusing on methane destruction through combustion. Scenarios S2 and S3 represent energy recovery pathways, where captured landfill gas is utilized for electricity generation and heat production with high utilization efficiency and gradual system ramp-up. Scenario S4 reflects a renewable natural gas system with the highest capture target and efficiency, indicating advanced upgrading of landfill gas into pipeline-quality fuel. Scenario S5 describes a low-flow utilization system designed for declining gas production conditions with moderate efficiency. Scenario S6 represents a landfill closure strategy with continued gas control through passive or limited recovery and partial oxidation improvement. Scenario S7 reflects a bioreactor landfill scenario characterized by enhanced biodegradation and higher gas capture potential through accelerated waste decomposition.

Table 6. Emission Calculation Results

Scenario	Year	CH_4 Potential (ton)	CH_4 Captured (ton)	CH_4 Destroyed (ton)	CH_4 Utilized (ton)	CH_4 Emitted (ton)	CO_2e Emitted (ton)
Scenario 0 Business as Usual	2015	–	–	–	–	–	–
	2016	1,116	–	–	–	1,116	27,893
	2017	2,001	–	–	–	2,001	50,021
	2018	2,713	–	–	–	2,713	67,837
	2019	3,295	–	–	–	3,295	82,373
	2020	3,776	–	–	–	3,776	94,390
	2021	4,213	–	–	–	4,213	105,313
	2022	4,573	–	–	–	4,573	114,332
	2023	4,883	–	–	–	4,883	122,081
	2024	5,143	–	–	–	5,143	128,572
	S0 Total	31,713	–	–	–	31,713	792,813
Scenario 1 Flare	2015	–	–	–	–	–	–
	2016	1,116	558	547	–	569	14,225
	2017	2,001	1,000	980	–	1,020	25,511
	2018	2,713	1,357	1,330	–	1,384	34,597
	2019	3,295	1,647	1,615	–	1,680	42,010
	2020	3,776	1,888	1,850	–	1,926	48,139
	2021	4,213	2,106	2,064	–	2,148	53,710
	2022	4,573	2,287	2,241	–	2,332	58,309
	2023	4,883	2,442	2,393	–	2,490	62,261
	2024	5,143	2,571	2,520	–	2,623	65,572
	S1 Total	31,713	15,856	15,539	–	16,173	404,334
Scenario 2 Electricity	2015	–	–	–	–	–	–
	2016	1,116	669	636	572	480	11,994
	2017	2,001	1,201	1,140	1,026	860	21,509
	2018	2,713	1,628	1,547	1,392	1,167	29,170

Scenario	Year	CH_4 Potential (ton)	CH_4 Captured (ton)	CH_4 Destroyed (ton)	CH_4 Utilized (ton)	CH_4 Emitted (ton)	CO_2e Emitted (ton)
	2019	3,295	1,977	1,878	1,690	1,417	35,421
	2020	3,776	2,265	2,152	1,937	1,624	40,588
	2021	4,213	2,528	2,401	2,161	1,811	45,285
	2022	4,573	2,744	2,607	2,346	1,967	49,163
	2023	4,883	2,930	2,783	2,505	2,100	52,495
	2024	5,143	3,086	2,931	2,638	2,211	55,286
	S2 Total	31,713	19,028	18,076	16,269	13,636	340,909
Scenario 3 Heat	2015	–	–	–	–	–	–
	2016	1,116	669	636	572	480	11,994
	2017	2,001	1,201	1,140	1,026	860	21,509
	2018	2,713	1,628	1,547	1,392	1,167	29,170
	2019	3,295	1,977	1,878	1,690	1,417	35,421
	2020	3,776	2,265	2,152	1,937	1,624	40,588
	2021	4,213	2,528	2,401	2,161	1,811	45,285
	2022	4,573	2,744	2,607	2,346	1,967	49,163
	2023	4,883	2,930	2,783	2,505	2,100	52,495
	2024	5,143	3,086	2,931	2,638	2,211	55,286
	S3 Total	31,713	19,028	18,076	16,269	13,636	340,909
Scenario 4 Emission Calculation	2015	–	–	–	–	–	–
	2016	1,116	474	469	446	172	4,302
	2017	2,001	1,276	1,263	1,200	313	7,822
	2018	2,713	2,306	2,283	2,169	430	10,752
	2019	3,295	2,801	2,773	2,634	522	13,056
	2020	3,776	3,209	3,177	3,018	598	14,961
	2021	4,213	3,581	3,545	3,368	668	16,692
	2022	4,573	3,887	3,848	3,656	725	18,122
	2023	4,883	4,151	4,109	3,904	774	19,350
	2024	5,143	4,371	4,328	4,111	815	20,379
	S4 Total	31,713	26,056	25,796	24,506	5,017	125,436
Scenario 5 Low Flow	2015	-	-	-	-	-	-
	2016	1,116	483	435	261	439	10,971
	2017	2,001	1,301	1,170	702	830	20,759
	2018	2,713	1,764	1,587	952	1,126	28,152
	2019	3,295	2,142	1,928	1,157	1,367	34,185
	2020	3,776	2,454	2,209	1,325	1,567	39,172
	2021	4,213	2,738	2,464	1,479	1,748	43,705
	2022	4,573	2,973	2,675	1,605	1,898	47,448
	2023	4,883	3,174	2,857	1,714	2,027	50,664
	2024	5,143	3,343	3,009	1,805	2,134	53,357
	S5 Total	31,713	20,371	18,334	11,001	13,137	328,413
Scenario 6 Closure	2015	–	–	–	–	–	–
	2016	1,116	781	765	153	317	7,922
	2017	2,001	1,401	1,373	275	568	14,206
	2018	2,713	1,899	1,861	372	771	19,266
	2019	3,295	2,306	2,260	452	936	23,394
	2020	3,776	2,643	2,590	518	1,072	26,807
	2021	4,213	2,949	2,890	578	1,196	29,909
	2022	4,573	3,201	3,137	627	1,299	32,470
	2023	4,883	3,418	3,350	670	1,387	34,671
	2024	5,143	3,600	3,528	706	1,461	36,514
	S6 Total	31,713	22,199	21,755	4,351	9,006	225,159
Scenario 7 Bioreactor	2015	-	-	-	-	-	-
	2016	1,116	595	565	452	253	6,322
	2017	2,001	1,601	1,521	1,217	480	12,005
	2018	2,713	2,171	2,062	1,650	651	16,281
	2019	3,295	2,636	2,504	2,003	791	19,770
	2020	3,776	3,020	2,869	2,296	906	22,654
	2021	4,213	3,370	3,202	2,561	1,011	25,275
	2022	4,573	3,659	3,476	2,781	1,098	27,440
	2023	4,883	3,907	3,711	2,969	1,172	29,299

Scenario	Year	CH_4 Potential (ton)	CH_4 Captured (ton)	CH_4 Destroyed (ton)	CH_4 Utilized (ton)	CH_4 Emitted (ton)	CO_2e Emitted (ton)
	2024	5,143	4,114	3,909	3,127	1,234	30,857
	S7 (Total)	31,713	25,072	23,819	19,055	7,596	189,903

Table 6 presents the results of methane emission simulations under different landfill gas management scenarios applied to Mandung Landfill. Under the Business-as-Usual condition, methane emissions continuously increase from 2016 to 2024, reflecting cumulative waste accumulation and the absence of any gas control measures, resulting in the highest total emissions across all scenarios. The Flare scenario shows a substantial reduction in emitted methane due to partial capture and destruction of landfill gas, leading to a significant decrease in total emissions compared to the baseline, although a considerable portion of methane is still released due to limited capture efficiency.

More advanced utilization scenarios, such as electricity and heat recovery, demonstrate similar emission reduction patterns, with higher levels of gas capture and utilization resulting in lower net methane emissions compared to flaring alone. The emission calculation scenario further reduces emissions by assuming higher overall efficiency in gas management and destruction processes, producing one of the lowest emission outcomes among the control scenarios. The Low Flow and Closure scenarios illustrate intermediate reductions, influenced by lower gas recovery efficiency or transitional landfill conditions, while still significantly reducing emissions compared to Business-as-Usual. The Bioreactor scenario provides a strong mitigation effect by enhancing methane generation control and capture efficiency, resulting in one of the lowest cumulative emissions overall. These results indicate that improved landfill gas management strategies can substantially reduce methane emissions, with higher capture and utilization efficiencies consistently producing greater mitigation benefits.

Table 7. SWOT Final Score

Component	S1	S2	S3	S4	S5	S6	S7
Strengths (S)	2.85	3.75	3.00	3.50	2.30	2.30	3.55
Opportunities (O)	2.60	3.60	3.00	4.00	2.00	2.00	3.80
S + O	5.45	7.35	6.00	7.50	4.30	4.30	7.35
Weaknesses (W)	2.20	3.80	3.00	4.00	1.20	1.80	4.00
Threats (T)	2.00	3.75	3.00	3.75	1.00	1.80	3.55
W + T	4.20	7.55	6.00	7.75	2.20	3.60	7.55
Final Score (S+O) − (W+T)	1.25	-0.20	0.00	-0.25	2.10	0.70	-0.20

Table 7 presents a quantitative SWOT-based evaluation of methane mitigation scenarios at TPA Mandung, developed from structured scoring by waste management practitioners. Each factor of Strength, Weakness, Opportunity, and Threat was weighted and scored to produce composite values (S+O) and (W+T), with the final score calculated as the difference between them. The results indicate that S5 (Low Flow Gas Management) is the most suitable scenario with the highest net score (2.1), reflecting its simplicity, low cost, and compatibility with existing landfill conditions. S6 (Closure) also shows a positive score (0.7) but remains limited due to the active operational status of the landfill. In contrast, S2, S4, and S7 yield negative or near-zero scores, indicating high technological, financial, and operational constraints despite strong potential benefits. S1 and S3 show marginal or neutral feasibility, suggesting limited effectiveness without a more stable gas collection system. The findings confirm that the most feasible mitigation strategy for TPA Mandung is a low-complexity, low-investment, and stepwise approach aligned with current operational realities, including basic landfill management improvements, source-level organic waste reduction, and gradual development of gas capture systems according to local capacity.

4.4. Projections of Solid Waste Generation and Implications

Solid waste generation projections were conducted to estimate future waste loads entering Mandung Landfill and their implications for methane emissions. Using a quantitative approach based on historical waste generation trends integrated with the IPCC First Order Decay (FOD) model, the study assumes that previously disposed waste continues to undergo anaerobic degradation, resulting in delayed and exponentially declining methane emissions over time. The model links waste accumulation, organic degradation characteristics, and time, allowing long-term methane emission projections beyond simple linear trend estimation. Consistent with IPCC guidelines, the results indicate that increasing population growth and socioeconomic activities in Tabanan Regency are expected to increase future waste generation and methane emission potential at Mandung Landfill.

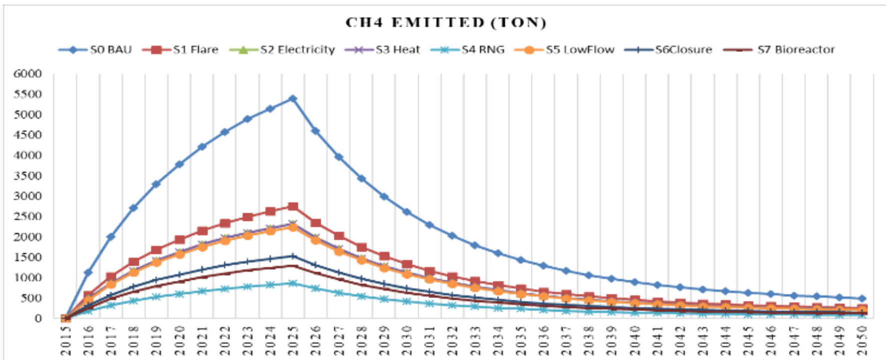

Figure 1. Methane Emission Projections Based on Scenarios

Figure 1 shows that methane emissions under the Business as Usual (BAU/S0) scenario increased gradually from 2016 and reached a peak during 2024–2025, with a maximum value of approximately 5,385 tons CH_4/year. This increase reflects the accumulation of solid waste from previous years entering the active anaerobic degradation phase. After reaching the peak, methane emissions gradually declined until 2050, although the landfill continued to generate significant emissions. This pattern is consistent with the characteristic exponential decay behavior of the IPCC First Order Decay (FOD) model, where emissions decrease as the biodegradable organic fraction becomes depleted over time.

All mitigation scenarios showed consistently lower emissions compared with the BAU scenario, although the reduction levels varied among scenarios. During the 2015–2050 period, cumulative methane emissions under BAU reached 75,389.18 tons CH_4, while mitigation scenarios significantly reduced emissions, particularly S4 (Renewable Natural Gas/RNG) with 11,940.19 tons CH_4, S7 (Bioreactor) with 18,078.53 tons CH_4, and S6 (Closure) with 21,410.53 tons CH_4. These results quantitatively indicate that technological and operational interventions in landfill management strongly influence long-term methane emission dynamics, even when future waste inputs decline.

The projections also demonstrate that methane emissions from landfilled waste are cumulative and long-term, meaning that waste disposed of in earlier years can continue contributing to emissions for decades. This finding highlights that delays in mitigation implementation may result in prolonged emission accumulation that becomes increasingly difficult to control in the future. The significant differences between the BAU and mitigation scenarios confirm that landfill gas utilization, bioreactor systems, and controlled landfill closure can reduce cumulative methane emissions by more than 70% compared with BAU. Therefore, quantitative projection-based waste management planning is essential for supporting regional greenhouse gas inventories and long-term methane mitigation strategies.

5. Discussion

The results of this study show that methane emissions from TPA Mandung, estimated using the First Order Decay (FOD) method with local parameters, exhibit a clear temporal distribution rather than an instantaneous release, following waste accumulation, anaerobic degradation, and exponential decay processes. The estimated emissions range from 1.12 to 5.14 Gg CH_4/year, indicating a substantial contribution of the waste sector to greenhouse gas emissions in Tabanan Regency. This high level is driven by increasing waste generation, a dominant organic fraction of approximately 60–65%, and the predominantly anaerobic landfill conditions, where limited gas capture systems result in uncontrolled methane release. These findings are consistent with studies in tropical landfill environments, where Suhardono et al. (2023) highlight that high temperature and humidity accelerate anaerobic decomposition, leading to higher methane generation rates, which aligns with the conditions observed in Bali. Furthermore, the temporal emission pattern in this study corresponds with the exponential degradation framework of FOD models, reinforcing the validity of using localized parameters such as DOC, k, and MCF, as emphasized by Citrasari et al. (2025), who demonstrate that local parameterization improves representativeness compared to IPCC default values. This dynamic approach is also supported by Janardanan et al. (2017), who argue that time-dependent modeling provides more realistic atmospheric emission estimates than static approaches.

The composition of waste plays a critical role in emission formation, where the dominance of biodegradable organic waste significantly increases DOC values and methane production potential. This is consistent with findings by Arisman and Iwan (2023), which show that waste in Bali is heavily dominated by organic fractions, resulting in elevated methane emissions. Sensitivity analysis in this study confirms that small changes in organic waste composition produce disproportionately large variations in methane output, consistent with Gunamantha et al. (2023), who reported emissions reaching 2562 Gg CO_2-e under baseline conditions and increasing to 5859 Gg CO_2-e with higher waste volumes. Similar patterns are observed in the Bengkala landfill, where methane production reaches approximately 68m^3 CH_4 per ton of waste, reinforcing that waste composition is a highly sensitive variable in emission estimation. These results confirm that local parameters and waste characteristics significantly influence emission magnitude and improve estimation accuracy compared to global defaults.

Scenario-based analysis further demonstrates that mitigation effectiveness varies significantly depending on the technological approach. Business-as-usual conditions show persistently high emissions, while mitigation scenarios such as flaring, landfill gas-to-energy, and bioreactor systems reduce emissions to varying degrees. Studies by Gunamantha et al. (2023) indicate that emissions can increase from 2562 to 5859 Gg CO_2-e under certain waste management conditions, while advanced gas capture scenarios can reduce emissions by up to 2929.5 Gg CO_2-e, highlighting the importance of intervention type. Similarly, research at Bengkala landfill shows reductions of 55% through flaring and up to 63% through energy recovery systems, demonstrating that more integrated technologies yield greater mitigation outcomes. These findings align with Razaviarani and Pushparajan (2025), who emphasize the dual benefit of landfill gas utilization for both emission reduction and renewable energy production.

Projected waste generation shows a steady increase from 79,235.89 tons in 2015 to 86,571.07 tons in 2024, mainly driven by population growth, leading to higher organic waste accumulation, increased DOC, and consequently greater methane emissions under the FOD framework. Consistent with studies by Citrasari et al. (2025) in tropical landfills, higher and more variable emissions are expected due to rapid degradation processes. Without improved management, TPA Mandung risks overcapacity and rising uncontrolled emissions, as also noted by Janardanan et al. (2017). Therefore, mitigation must go beyond end-of-pipe approaches and integrate upstream waste reduction and improved landfill operations, including gas capture and optimized decomposition control, as recommended by Przydatek et al. (2024). The findings confirm that methane emissions are strongly driven by waste quantity, composition, and local operational conditions, while validating that locally parameterized FOD modeling provides a robust basis for both emission estimation and mitigation planning.

6. Conclusion

The findings of this study indicate that methane emissions from TPA Mandung, estimated using a locally calibrated IPCC First Order Decay (FOD) model, exhibit a cumulative and time-dependent pattern consistent with waste accumulation and anaerobic degradation processes. Emissions range from 1.12 to 5.14 Gg CH_4/year, highlighting the substantial contribution of the landfill sector to regional greenhouse gas emissions. The results demonstrate that methane generation is strongly driven by increasing waste quantities, a high proportion of biodegradable organic waste, and limited gas capture systems under tropical landfill conditions. Sensitivity analysis further confirms that waste composition, particularly organic fractions, significantly influences emission magnitude, reinforcing the importance of local parameterization in improving estimation accuracy compared to default IPCC assumptions. Scenario analysis shows that mitigation strategies such as flaring, energy recovery, landfill closure, and bioreactor systems can substantially reduce emissions, with advanced systems achieving reductions of more than 60–70% compared to the business-as-usual condition.

This study has several implications for landfill management and climate mitigation policy. The results emphasize the urgency of implementing integrated landfill gas management systems and upstream waste reduction strategies to minimize long-term methane emissions. However, the study is limited by reliance on secondary data, the use of static waste composition for certain years, and deterministic modeling assumptions that do not fully capture operational variability and measurement uncertainty. Future research should incorporate field-based methane measurements, dynamic waste composition tracking, and hybrid modeling approaches combining IPCC FOD with process-based or machine learning models. In addition, techno-economic and policy feasibility assessments are needed to support the selection of optimal mitigation pathways tailored to local landfill conditions in tropical developing regions.

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Ethical approval was obtained for this study. The manuscript represents original work and has not been previously published, nor is it under consideration by another journal.

Data Disclosure Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.