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Dispersion modelling of methane emissions from Indonesian landfills using air quality dispersion modeling

Nita Citrasari[1,2*], Chita Melati Ghea Wasturani[2], Clarissa Dinda Ayu Zahra[2], Dwi Ratri Mitha Isnadina[2], Sucipto Hariyanto[3], Muhammad Abdus Salam Jawwad[4], Indriyani Rachman[1,5], Toru Matsumoto[1]

[1] Graduate Programs in Environmental Systems, Graduate School of Environmental Engineering, The University of Kitakyushu, Kitakyushu 808-0135, Japan
[2] Environmental Engineering Program, Department of Biology, Faculty of Science and Technology, Universitas Airlangga, Surabaya 60115, Indonesia
[3] Biology Program, Department of Biology, Faculty of Science and Technology, Universitas Airlangga, Surabaya 60115, Indonesia
[4] Department of Environmental Engineering, Faculty of Engineering, Universitas Pembangunan Nasional "Veteran" Jawa Timur, Surabaya 60294, Indonesia
[5] Department of Natural Science Education, School of Postgraduate Studies, Universitas Pakuan, Bogor 16143, Indonesia
[6] Research Centre for Urban Energy Management, Institute of Environmental Science and Technology, The University of Kitakyushu, Kitakyushu, 808-0135, Japan
* Corresponding author's e-mail: nita-c@fst.unair.ac.id

ABSTRACT

Methane emissions from landfills pose a growing environmental challenge in Indonesia, where the increasing generation of waste is met by limited monitoring of these emissions. As one of the most significant anthropogenic sources of methane, landfills contribute significantly to national greenhouse gas (GHG) emissions. This study examines the spatial distribution, temporal variation, and comparative dispersion patterns of methane from two landfills, Griyomulyo and Sekoto, utilizing AERMOD (air quality dispersion modeling) modeling. Spatial delineation (2006–2024) and emission estimates from four models (IPCC, LandGEM, Afvalzorg, and Thailand) were input into 24-hour and 1-month simulations for 2021, 2022, and 2025. Dispersion outputs were overlaid with village boundaries to identify communities within high-exposure zones. Griyomulyo exhibited broader dispersion due to higher waste generation and flat topography, while Sekoto showed more localized and less intense patterns. In the Thailand 2025 scenario (24-hour, 500 µg/m³ threshold), Griyomulyo's plume reached 20,268.9 meters, covering 24,194 hectares and affecting 11 villages – over twice the extent of Sekoto. Dispersion behavior varied based on model choice, simulation duration, and site-specific conditions. These findings highlight the spatial variability of landfill methane emissions and emphasize the need for location-specific assessments to support sustainable mitigation strategies in Indonesia's solid waste sector.

Keywords: methane emissions; landfill sites; dispersion modelling; AERMOD simulation; Indonesia.

INTRODUCTION

Landfills are significant contributors to methane emissions, accounting for approximately 18 percent of global anthropogenic methane emissions and 3.8 percent of total greenhouse gas (GHG) emissions (Intergovernmental Panel on Climate Change). Methane (CH_4) has a global warming potential 28 times higher than carbon dioxide (CO_2) over a 100-year period. Despite its relatively short atmospheric lifetime (around 9.1 years), it exerts strong radiative forcing and plays a significant role in global climate change and local environmental degradation. (Olaguer et al., 2022; Scharff et al., 2024; UNFCCC, 2021; Wu et al., 2023). Beyond global effects, methane emissions influence microclimates by increasing local temperatures and degrading air quality (Cusworth et al., 2024). Methane also acts as a precursor to ground-level ozone (O_3), produced through photochemical reactions with hydroxyl radicals (OH), carbon monoxide (CO), and formaldehyde (HCHO), contributing to urban air pollution (Mønster et al., 2019). In Indonesia, methane emissions from landfills remain largely unmonitored due to the absence of landfill gas (LFG) collection systems, minimal compaction, and non-engineered infrastructure. As waste generation rises, landfill expansion continues, yet emission monitoring and mitigation strategies remain limited. Methane emissions from landfills can reach up to 3000 kg/h and disperse beyond site boundaries due to meteorological and topographic influences (Balogun-Adeleye et al., 2019; Delkash et al., 2022; Mønster et al., 2019; Olaguer et al., 2022). Understanding the spatial and temporal dispersion patterns of methane emissions is crucial for effective landfill management, reducing greenhouse gas (GHG) emissions, and aligning with national climate goals.

A few studies have simulated landfill methane dispersion at the site level, but most research in Indonesia remains fragmented (Wijaya et al., 2021). A recent national also confirmed that methane emissions from landfills are under-monitored and rarely linked to spatial exposure modeling (Citrasari et al., 2025). This study addresses that gap by integrating four emission estimation models—IPCC, LandGEM, Afvalzorg, and Thailand Model—with AERMOD (air quality dispersion modeling) simulations for two contrasting landfill sites. It is the first to compare multi-model dispersion across sites and visualize exposure at the settlement level, supporting early warning and targeted mitigation planning. This study aims to enhance the understanding and management of methane emissions from Indonesian landfills by utilizing the AERMOD dispersion model. Specifically, the objectives are threefold. First, to analyze the spatial distribution of methane emissions, including the extent and direction of dispersion influenced by local meteorological conditions. Second, to evaluate the temporal variation by simulating different operational years, thereby identifying changes in dispersion behavior over time. Third, to compare emission dispersion patterns between Griyomulyo and Sekoto landfills, which differ in scale and site conditions, in order to inform more effective, site-specific mitigation strategies. Unlike studies that focus solely on methane generation estimation, this research integrates four established models: the IPCC, LandGEM, Afvalzorg, and the Thailand Model, along with AERMOD, to simulate methane dispersion more accurately (Afvalzorg, 2023; Alexander et al., 2005; Bartram and Towprayoon, 2019; Global Methane Initiative (GMI), 2004; Intergovernmental Panel On Climate Change (IPCC), 2023; P.E. and Lloyd, 2009; Wang, Fang, et al., 2024). AERMOD incorporates meteorological parameters, source characteristics, and terrain features to predict both short- and long-term dispersion patterns (U.S. Environmental Protection Agency, 2024a, 2024b).

Evidence from both Indonesian and international studies underscores the need for spatial dispersion modeling that extends beyond static emission estimates. At Sarimukti Landfill, projected methane emissions were 11,462 Mg/year (IPCC) and 14,810 Mg/year (LandGEM) by 2025 (Wijaya et al., 2021). At Winongo, 45,667 tons of waste disposed of in 2024 generated up to 15,190 kg of CH_4 (Sumarlin et al., 2023). Internationally, drone-based Gaussian modeling at two landfills in Michigan, USA, showed methane fluxes of ~500 kg/h (~4,380 Mg/year) (Matacchiera et al., 2019; Olaguer et al., 2022). These examples emphasize the importance of dispersion modeling for effective landfill gas management. Effective methane management is crucial for mitigating environmental and health impacts. Strategies such as landfill gas (LFG) collection systems, waste compaction, engineered covers, and microbial methane oxidation can reduce emissions. For example, the Klintholm Landfill in Denmark successfully used gas trenches and compost bio-covers to limit methane release (M. A. Budihardjo, 2012; Scheutz et al., 2022). Identifying high-emission zones through dispersion modeling supports more resilient landfill planning and contributes to both climate action and sustainable waste management (Barlaz et al., 2009; Budihardjo et al., 2021; Budihardjo, 2012; Cao and Staszewska, 2013; Chan et al., 2023; Fraser-McDonald et al., 2022; Meyer-Dombard et al., 2020; Scheutz et al., 2014). This approach contributes to achieving sustainable development goals (SDGs) 11 (Sustainable Cities and Communities) and 13 (Climate Action) through integrated waste and emission management (Dagnachew et al., 2021; Gusheva et al., 2022). A case study from the Deonar dumpsite in Mumbai demonstrated that landfill gas (LFG) flaring could be implemented as early as the second year of landfill operation. The pre-feasibility study indicated that gas could be collected from a 40-hectare area with a maximum flow rate of 3.900 m³/h, and the system was planned to operate for 44 years (Yaashikaa et al., 2022).

MATERIALS AND METHODS

Study location

This study was conducted at two municipal landfills in East Java Province, Indonesia: Griyomulyo Landfill in Sidoarjo Regency and the Sekoto Landfill in Kediri Regency. Griyomulyo underwent an expansion in 2020, while Sekoto began operating a new disposal cell in 2021. Both sites function as controlled landfills, with Griyomulyo receiving approximately 450 Mg/day of waste and Sekoto handling 100–105 Mg/day (DLH-Kediri Regency & ITS, 2022, 2023; Ramadhaningsih, 2021). These expansions were driven by increasing waste generation and the limited remaining capacity of the original landfill zones.

Landfill area delineation

Landfill boundaries were manually delineated using annual satellite imagery from Google Earth Pro (2006–2024), following a five-step approach (Gage et al., 2020). This included data acquisition, georeferencing to WGS 1984 UTM Zone 49S, on-screen digitization (ArcGIS 10.8 and QGIS 3.22), area calculation (hectares), and consistency validation across the time series. Multi-year imagery enabled temporal tracking of disposal zone changes, supported by ground-truth validation through direct coordination with landfill operators (Papale et al., 2023). Surface differences were visually identified using color changes, and final maps were enhanced with scale bars, north arrows, and legends. All spatial data were projected to UTM Zone 49S (EPSG: 32749), which is the appropriate coordinate system for East Java. Year-on-year percentage changes in disposal areas were calculated to identify growth, stagnation, or decline. Method limitations include manual tracing subjectivity, image resolution variability, and cloud cover interference (Balogun-Adeleye et al., 2019; Gage et al., 2020; Kumar et al., 2023; Papale et al., 2023; Scheutz et al., 2022; Wijaya et al., 2021).

Methane dispersion modeling and spatial interpretation using AERMOD and GIS

Methane dispersion was modeled using AERMOD, with meteorological input derived from the ERA5 reanalysis dataset (Climate Data Storage, 2024). Key parameters included total cloud cover, temperature, relative humidity, pressure, wind speed and direction, ceiling height, precipitation, and solar radiation. These were processed using AERMET to produce the.SFC and.PFL files representing surface and upper-air conditions (Ho and Nguyen, 2025; Kalhor and Bajoghli, 2017; Kumar et al., 2021; Matacchiera et al., 2019; U.S. Environmental Protection Agency, 2024a, 2024b). Methane emission inputs were estimated using four models: IPCC, LandGEM, Afvalzorg, and the Thailand Model. Each landfill was modeled as an area source with a Cartesian grid of receptors. Emission source coordinates were placed at multiple representative points within each landfill and applied consistently across all model simulations. The receptor grid was fixed at 30 × 30 km across all scenarios. All spatial components—including source and receptor locations—were projected using UTM Zone 49S (EPSG:32749), based on WGS 84. Simulations were conducted for two durations, 24 hours (24H) and 1 month (1M), to reflect short-term accumulation and longer-term exposure (Matacchiera et al., 2019; Olaguer et al., 2022; Scheutz and Kjeldsen, 2019; Wijaya et al., 2021). A total of 32 AERMOD scenarios were modeled, covering two sites (Griyomulyo and Sekoto), two years per site (2021 and 2025 for Griyomulyo; 2022 and 2025 for Sekoto), four emission models, and two durations. Post-processing was conducted in ArcGIS by overlaying AERMOD contour maps (μg/m³) onto georeferenced base layers, including village boundaries, roads, and rivers (Liu and Nijhuis, 2020). Areas exceeding 500 μg/m³ were delineated and measured in hectares using the measure area tool. Maximum dispersion distances were recorded from the central point of each landfill to the furthest edge of the contour.

RESULTS AND DISCUSSION

Landfill expansion and its relationship to potential methane emission

Figure 1 shows the annual delineation of Griyomulyo and Sekoto Landfills from 2006 to

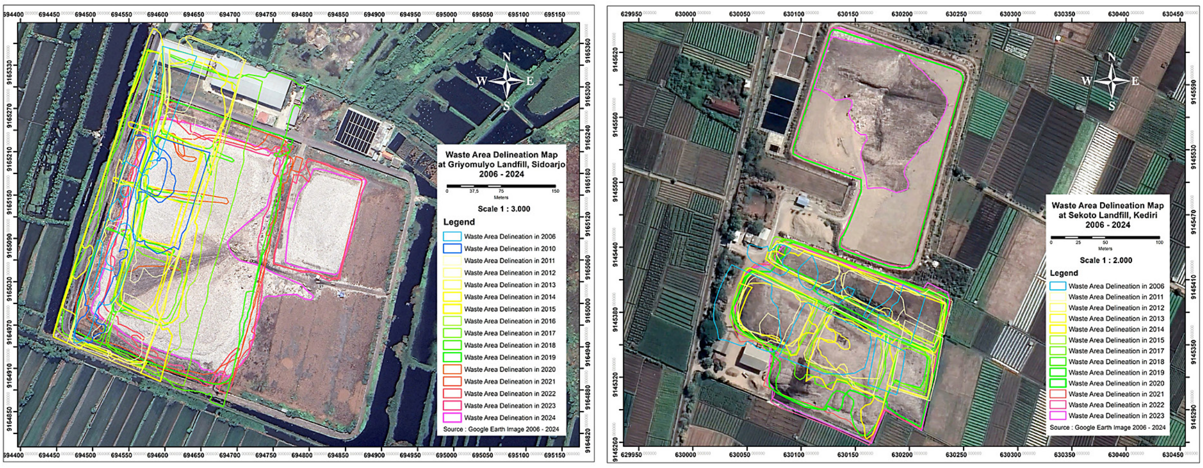

Figure 1. Annual delineation of Griyomulyo and Sekoto Landfills (2006 to 2024)

2024, highlighting growth trends based on spatial expansion. Griyomulyo experienced rapid early expansion, with the highest annual increase of +86.38% in 2011, the most significant decrease of -21.36% in 2019, and a peak area of 9,535.00 Ha in 2018, up from 1,806.00 Ha in 2010. In contrast, Sekoto exhibited slower initial growth but recorded a sharp increase of 60.13% in 2023, reaching 3,803.00 Ha, compared to under 1,300.00 Ha from 2006 to 2012. After 2021, Griyomulyo followed a more stable expansion pattern, while Sekoto remained in an active growth phase through 2023, reflecting a newer stage of development.

These contrasting delineation results suggest a correlation between increasing waste volume and the expansion of landfills (Bahraini, 2022; Hasjanah, 2023). Due to limited land, most landfills apply cell and lift systems to optimize space. (Construction, 2022; Environment Protection Authority Victoria, 2015). In Griyomulyo, the negative value in 2019 reflects operational shifts between lifts within existing zones rather than actual area reduction. Similar transitions occur in landfills using one-lift-per-year systems, such as Tara-tara landfill or vertical expansion, as seen in Xi'an, China, causing fluctuations in delineation due to internal reallocation rather than external expansion (Panagiotakopoulos and Dokas, 2001; Polii et al., 2020; Sheng et al., 2021).

Indonesia's growing waste generation, driven by population growth, urbanization, the pandemic, and modern lifestyles, explains the recent acceleration at the Sekoto landfill (Muis et al., 2024; Muis et al., 2024; Olawade et al., 2024; Ruslinda et al., 2021). These patterns provide insights into the potential for methane emissions, primarily from the anaerobic decomposition of organic waste in active cells (Bains et al., 2023; Olaguer et al., 2022; Oonk, 2010). As landfills age, surface exposure and methane release increase (Sheng et al., 2021). New, uncapped zones emit more, while capped areas emit less. For example, Winongo emitted 15,190 kg CH_4 in 2024 from 45,667 tons of waste, while Toisapu is projected to release 6,800 tons of CH_4 between 2008 and 2026 (Sumarlin et al., 2023). These findings underscore the importance of understanding operational dynamics when interpreting delineation. Spatial delineation is a crucial input for AERMOD-based methane dispersion modeling, supporting sustainable, site-specific landfill management strategies.

Spatial distribution of methane emissions

Figures 2a and 2b illustrate methane dispersion patterns across multiple simulation years, specifically the first year after landfill operation and the most recent year (2025), where methane emissions are assumed to have already been generated under anaerobic decomposition conditions. The 2025 scenarios consistently exhibit broader plumes, higher concentrations, and wider exposure zones, particularly at Griyomulyo, reflecting cumulative effects of waste accumulation, landfill expansion, and operational age. Based on these findings, Figures 3 through 6 focus on the 2025 simulations as the most relevant representation of present-day methane dispersion at both sites.

Figure 3a shows the relationship between methane concentration thresholds and exposed areas in Griyomulyo and Sekoto. As thresholds

Figure 2. (a) Methane dispersion maps for Griyomulyo Landfill were generated using AERMOD, based on four emission estimation models (IPCC, LandGEM, Afvalzorg, and Thailand) across two simulation years (2021 and 2025) and two durations (24 hours and 1 month). Labels (a–d) represent IPCC-based simulations, (e–h) LandGEM, (i–l) Afvalzorg, and (m–p) Thailand model. (b) Methane dispersion maps for Sekoto Landfill were generated using AERMOD, based on four emission estimation models (IPCC, LandGEM, Afvalzorg, and Thailand) across two simulation years (2022 and 2025) and two durations (24 hours and 1 month). Labels (a–d) represent IPCC-based simulations, (e–h) LandGEM, (i–l) Afvalzorg, and (m–p) Thailand model

increase, the exposed area decreases, ranging from over 54,000 hectares at 500 μg/m³ (Griyomulyo, IPCC 24H) to under 1.000 hectares near 90,000 μg/m³. Griyomulyo consistently exhibits a broader spread, particularly in 24-hour simulations using the IPCC and Thailand models. Its lower topography and location nearer the coast may influence this pattern, allowing for the lateral expansion of affected zones. In contrast, 1-month durations, particularly with Afvalzorg and Thailand, produce

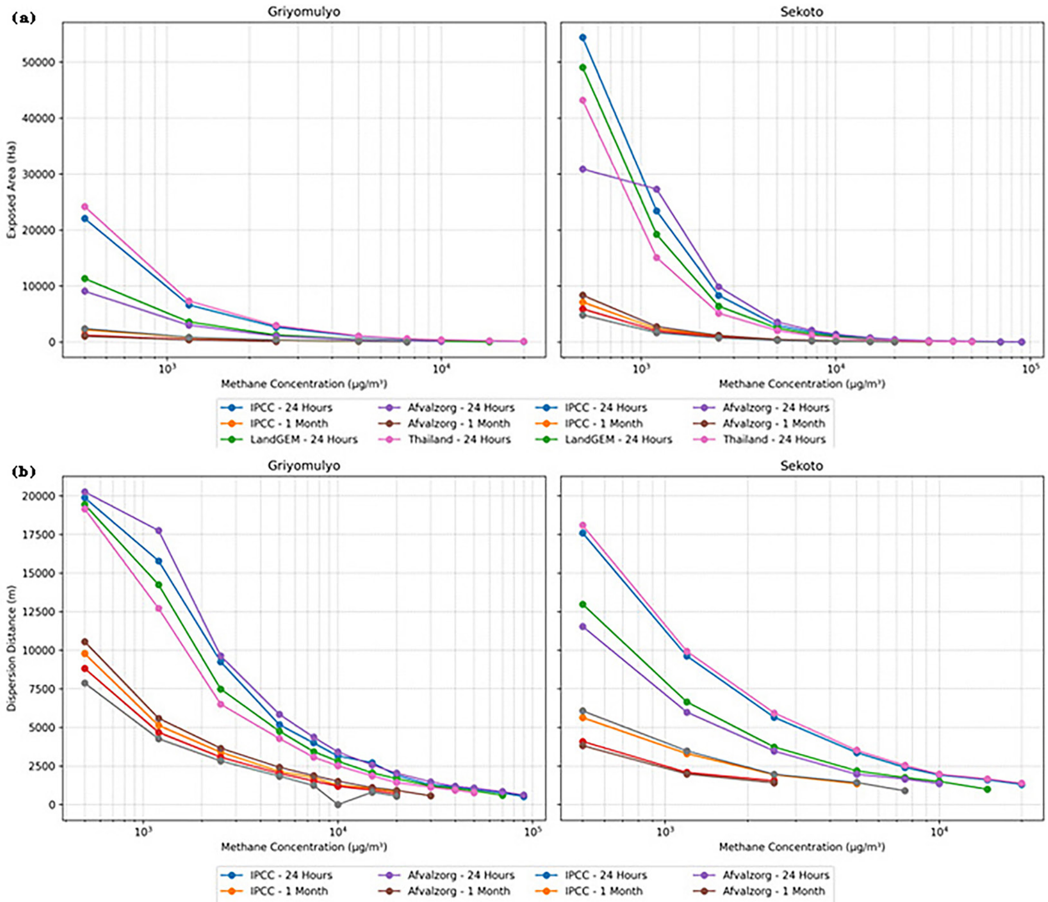

Figure 3. Methane concentration thresholds (2025) in Griyomulyo and Sekoto Landfills: (a) exposed area, (b) dispersion distances

more confined areas, generally below 10.000 hectares. Sekoto exhibits similar trends, with most results below 5.000 hectares and above 5.000 µg/m³. These findings confirm that the exposed area is inversely related to the threshold level and varies across models and simulation durations.

Figure 3b shows the relationship between methane concentration thresholds and dispersion distances in Griyomulyo and Sekoto. As thresholds increase, distances decrease, from up to 20,269 meters at 500 µg/m³ (Griyomulyo, Thailand 24H) to below 650 meters near 90,000 µg/m³. Griyomulyo shows a more extended reach, with IPCC and Thailand (24H) exceeding 18,000 meters. In contrast, Sekoto's elevated setting may contribute to shorter dispersion distances despite similar modeling inputs. One-month durations, particularly with Afvalzorg and Thailand, remain below 8.000 meters across thresholds. Sekoto follows a similar pattern, with most results under 15,000 meters at low thresholds and below 5000 meters at concentrations above 10.000 µg/m³. These findings confirm that dispersion distance is inversely related to concentration level and influenced by model type and simulation duration.

Temporal variation of methane emissions

Temporal variation in methane emissions is evident across all models, with 24-hour simulations consistently producing higher peak concentrations than 1-month durations. Maximum concentrations ranged from 500 to 90,000 µg/m³, depending on the model and landfill site. Griyomulyo showed stronger contrasts, reflecting sustained methane generation and a larger emission baseline, while Sekoto's outputs remained more stable over time.

Figures 4 and 5 present methane dispersion across surrounding villages. In Griyomulyo, 11 villages were affected in 2025. Kupang, Balongtani, and Tambak Kalisogo lie in the highest concentration zone (≥ 10,000 µg/m³), followed by Puhjarak, Kemiri, Kedungbendo, and Kedung Peluk (5000–7500 µg/m³), and Permisan, Semambung, Plumbon, and Banjarsari (500–1200 µg/m³).

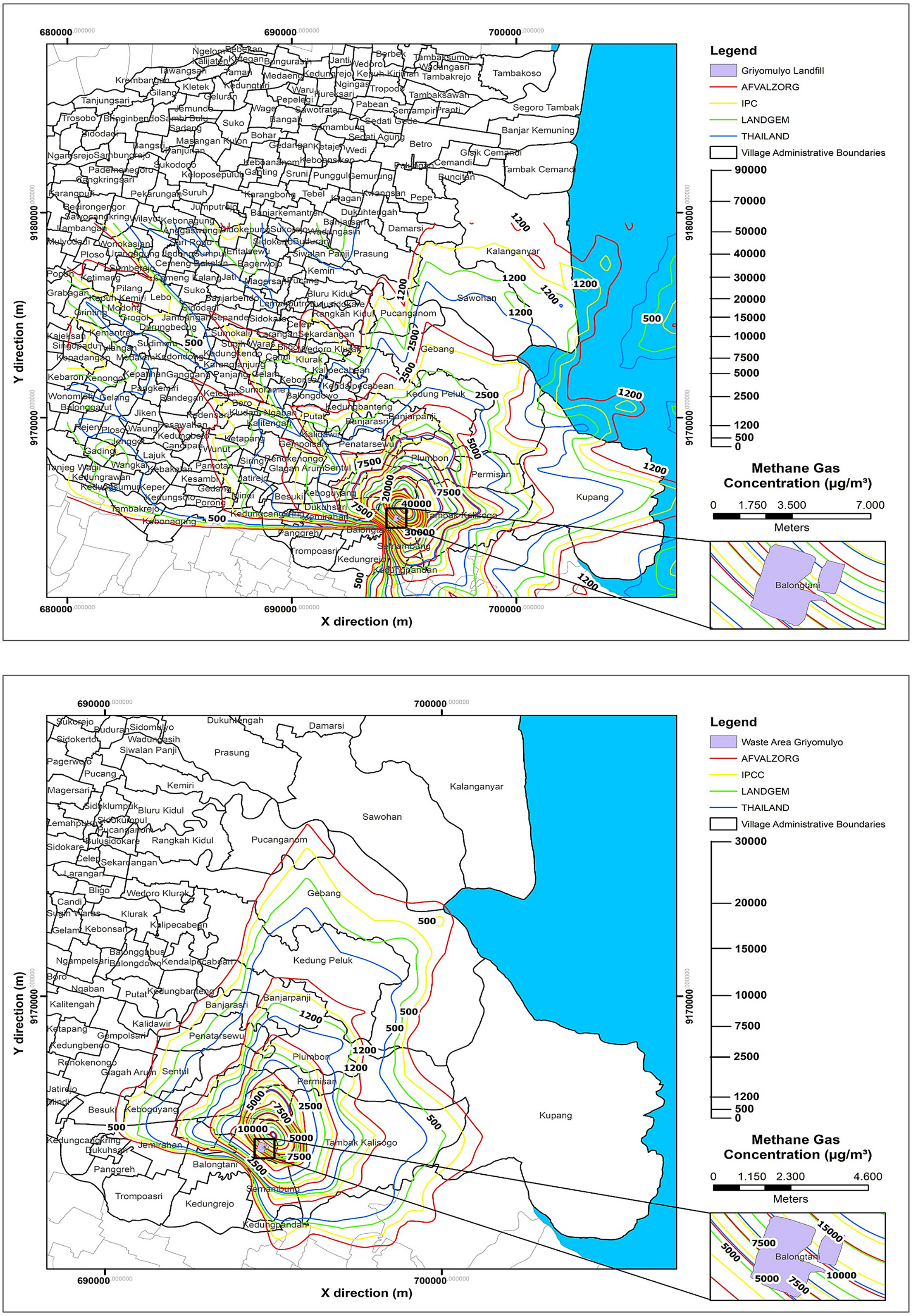

Figure 4. Methane dispersion contours for Griyomulyo Landfill in 2025 (Afvalzorg Model, 500 µg/m³). The 24-hour (top) contour shows a broader spread, and the 1-month (bottom) contour shows a more confined pattern

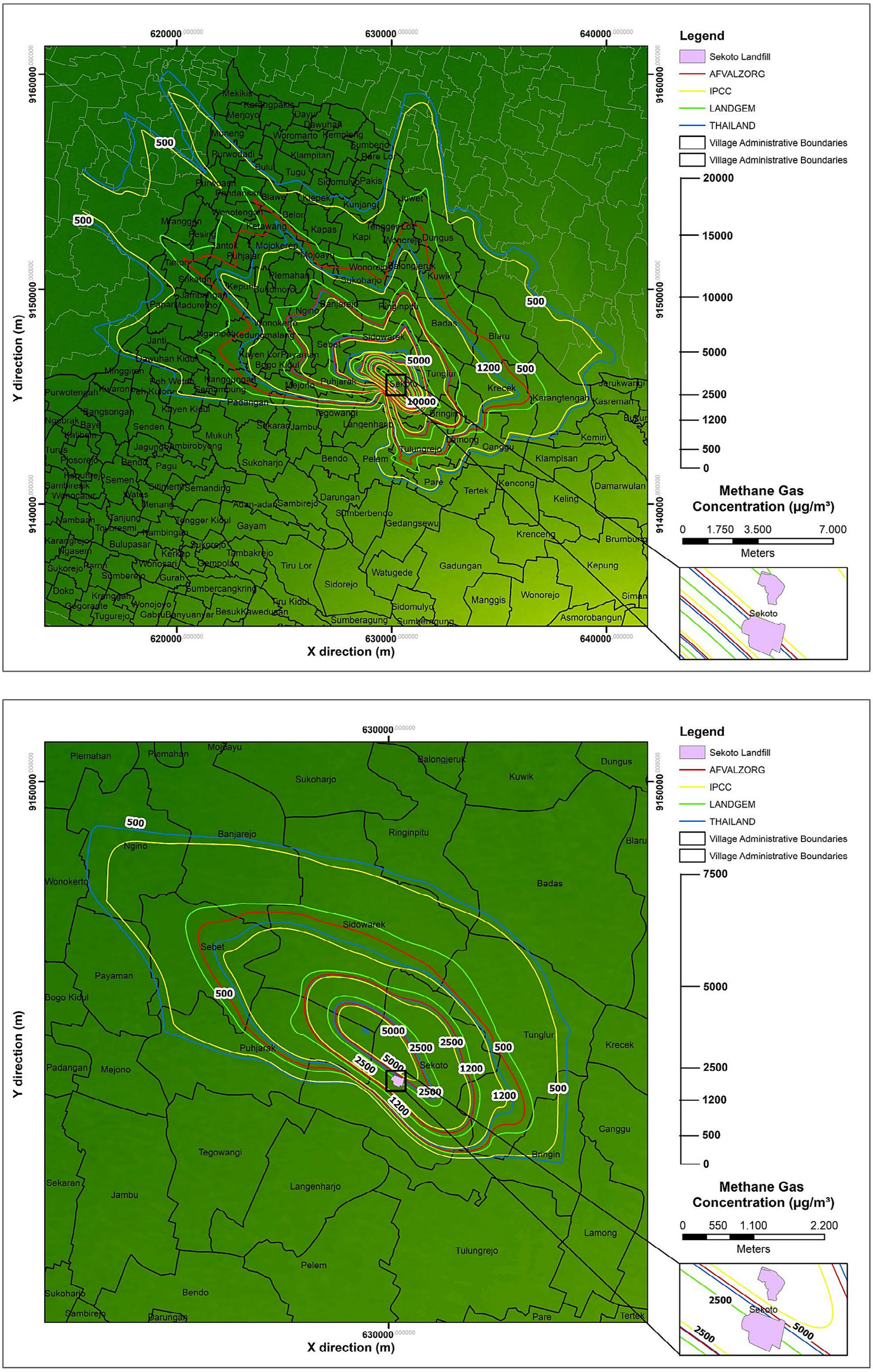

Figure 5. Methane dispersion contours for Sekoto Landfill in 2025 (Afvalzorg Model, 500 µg/m³). The 24-hour (top) contour shows a broader spread, and the 1-month (bottom) contour shows a more confined pattern

Penatarsewu, located northeast, is only impacted in extended dispersion cases. In Sekoto, seven villages appear in the exposure zones. Sekoto and Puhjarak fall within 5000–10,000 µg/m³, Sidowarek and Selet within 2500–5000 µg/m³, and Tunglur, Ringinpitu, and Blaru within 500–1200 µg/m³, though the last two are simulation-dependent. The patterns confirm that landfills are significant sources of methane, with dispersion influenced by emission strength, wind direction, and topography.

Comparison between Griyomulyo and Sekoto landfills

Methane dispersion differences between Griyomulyo and Sekoto stem from three factors: landfill siza, waste age, and cumulative organic accumulation (Toha et al., 2025; Yeşiller et al., 2022). Larger landfills, such as Griyomulyo, with broader active zones and more organic input, tend to produce wider and more intense plumes. In contrast, Sekoto's smaller size and lower input result in more localized emissions. Emission levels also depend on the anaerobic decomposition stage; methane typically begins forming about six months after disposal, peaks within 1–10 years, and declines thereafter, highlighting the role of waste age in shaping emission behavior and supporting the choice of 2021 and 2022 as simulation baselines. (Jensen and Pipatti, 2023; Krause et al., 2023; U.S. EPA, 2023).

The AERMOD simulations revealed distinct differences between Griyomulyo and Sekoto in terms of methane dispersion intensity, spatial extent, and the number of affected villages. Griyomulyo exhibited broader plumes and longer dispersion distances, with exposed areas exceeding 24,000 hectares and dispersion reaching over 18 kilometers, particularly under IPCC and Thailand 24-hour simulations. These outcomes are attributed to higher waste generation, older decomposition profiles, and flat coastal topography, which allowed horizontal plume expansion. In contrast, Sekoto's emissions were more concentrated and spatially contained, shaped by its smaller size and surrounding elevated terrain (Balogun-Adeleye et al., 2019; Bingemer and Crutzen, 1987; Chiemchaisri et al., 2005; Delgado et al., 2023; Talaiekhozani et al., 2018). Simulation duration also played a role: short-term runs produced wider plumes due to peak concentration loads and limited atmospheric decay. At the same time, 1-month durations resulted in narrower contours due to temporal averaging effects (U.S. EPA, 2024).

AERMOD simulations made these model-based distinctions visible by translating methane generation estimates into measurable spatial impacts. Model type further shaped dispersion outcomes. IPCC and LandGEM generated the widest impact zones based on global assumptions and high-end projections. In contrast, the Thailand Model consistently produced shorter plumes, particularly in 1-month simulations, aligning with tropical decay rates and reducing emissions during the landfill's late operational phase. Afvalzorg yielded balanced results, integrating conservative assumptions with regional adjustments (Delkash et al., 2016; Jittra et al., 2015; Matacchiera et al., 2019; Popoola et al., 2022; U.S. Environmental Protection Agency, 2024a, 2024b; Vaverková, 2019; Wang et al., 2024; Wang, Zhou, et al., 2024; Wangyao, 2010). These outcomes underscore the need to select estimation models based on site-specific conditions and data availability, supporting effective national methane monitoring and planning (Dagnachew et al., 2021; Toha et al., 2025; Zhang et al., 2024; Zimnoch et al., 2019).

The results reinforce the value of threshold-based mapping as an early warning tool for gas accumulation risks (Barlaz et al., 2009; Chandra and Ganguly, 2023; Citrasari et al., 2025; Kumar et al., 2023; Manheim et al., 2021, 2024; Nisbet et al., 2020). These findings highlight the need for location-specific, risk-based strategies that combine continuous monitoring, gas capture or flaring, and adaptive controls such as bio-covers, passive venting, and perimeter gas barriers (Bian et al., 2018; Cao and Staszewska, 2013; Chan et al., 2023; Moshkal et al., 2024; Thompson et al., 2009; Warmadewanthi et al., 2021). Gas capture enables energy recovery but requires higher costs and technical capacity while flaring is more affordable, highly efficient (> 99% for enclosed flares), and suitable for smaller or low-infrastructure sites (CED engineering, 2020; Krause et al., 2023; Mor et al., 2024; Wang et al., 2024). Complementary practices such as daily cover and organic waste diversion can further reduce emissions by 70–90%, improve safety, and support energy utilization (Rudd et al., 2024; Scharff et al., 2024). These mitigation options should be tailored to site conditions—for instance, perimeter gas barriers and passive venting may be suitable for Sekoto's localized emissions. In contrast, adaptive flaring and gas capture are more applicable to

Griyomulyo's broader and more intense dispersion patterns (Garland and Frankiewicz, 2023). Flaring remains cost-effective (US$1.921/kW; US$5/ton CO_2-eq; approximately US$4.500/year) and is becoming increasingly viable in developing countries through carbon credit mechanisms. (Project Drawdown, 2025; Thunder Said Energy, 2025; World Bank, 2020).

LIMITATION OF THE STUDY

This study was limited in scope to modeling methane dispersion from only two landfill sites using selected emission models and available meteorological inputs. These findings represent a temporal snapshot shaped by evolving landfill operations and climatic conditions, underscoring the need for periodic monitoring and model refinement to ensure sustained accuracy and reliability. Additionally, the spatial interpretation was operationally limited to the year 2025, selected for its relevance to current landfill planning and as the maximum projection year supported by all emission models used, ensuring consistency and comparability of the results.

CONCLUSIONS

Methane emissions from Indonesian landfills can affect areas exceeding 54,000 hectares, dispersed over 20 kilometers, and impact up to 11 surrounding villages, reaching concentrations as high as 90,000 µg/m³—indicating the need for spatially targeted mitigation strategies. These findings represent a temporal snapshot shaped by evolving landfill operations and climatic conditions, underscoring the importance of periodic monitoring and model refinement to ensure accuracy and relevance. AERMOD simulations have proven effective in translating methane generation estimates into spatial exposure patterns, enabling evidence-based decision-making in emission control. Among mitigation options, flaring systems have been reported as a cost-effective solution (US$ 1.921/kW; US$ 5/ton CO_2-equivalent; approximately US$ 4.500 per year) and are increasingly viable in developing countries through carbon credit mechanisms. Threshold-based mapping, combined with site-specific mitigation measures such as flaring, gas capture, bio-covers, and organic waste separation, offers an efficient, scalable, and energy-recoverable approach that also enhances environmental safety and early warning capabilities. However, the limited national data infrastructure and the absence of locally calibrated models remain significant barriers, underscoring the need to strengthen an integrated mitigation framework that is aligned with technological capacity, socio-economic conditions, and site-specific characteristics in Indonesia.

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