Prepublished Copy

NATURE ENVIRONMENT AND POLLUTION TECHNOLOGY

Article In Press

PEER-REVIEWED PREPUBLISHED MANUSCRIPT

This is a peer-reviewed prepublished version of the paper to be published in **Vol. 26, No. 1, March 2027.**

Integrated Emission Inventory and Mitigation Strategies for Air Pollutants and Greenhouse Gases in the Waste Sector: A Case Study of Semarang City

Bimastyaji Surya Ramadan, Nurandani Hardyanti, Dyah Ika Rinawati, Anik Sarminingsih and Yim Mongtoeun

RECEIVED
23 July 2026

CITE THIS ARTICLE

Ramadan, B.S., Hardyanti, N., Rinawati, D.I., Sarminingsih, A. and Mongtoeun, Y., 2027. Integrated Emission Inventory and Mitigation Strategies for Air Pollutants and Greenhouse Gases in the Waste Sector: A Case Study of Semarang City. *Nature Environment and Pollution Technology*, 26(1), D1965.

https://doi.org/10.46488/NEPT.2027.v26i01.D1965

EARLY-ACCESS STATEMENT

This manuscript, after peer review, is being released online in its original, unedited form to provide early access to its findings. Prior to final publication, it will undergo additional editing and formatting. Readers may note that, as an unedited version, the manuscript may have linguistic and other minor errors. The DOI will be active after the final publication of the paper.

PUBLICATION STATUS

PEER REVIEW	ONLINE VERSION	FINAL ISSUE
Completed	**Prepublished**	**March 2027**

© The Author(s) 2027. This article is Open Access under the Creative Commons Attribution 4.0 International License, allowing use, sharing, adaptation and reproduction with proper credit. Images or third-party material are covered by this licence unless otherwise noted. For uses beyond the licence, permission must be obtained from the copyright holder. Licence details: creativecommons.org/licenses/by/4.0/.

Original Research

Integrated Emission Inventory and Mitigation Strategies for Air Pollutants and Greenhouse Gases in the Waste Sector: A Case Study of Semarang City

Bimastyaji Surya Ramadan[1]†, Nurandani Hardyanti[1], Dyah Ika Rinawati[2], Anik Sarminingsih[1], and Yim Mongtoeun[3]

[1] Department of Environmental Engineering, Universitas Diponegoro, Semarang, 57127, Indonesia

[2] Department of Industry Engineering, Faculty of Engineering, Universitas Diponegoro, Semarang 50275, Indonesia

[3] 3 Royal University of Phnom Penh (RUPP), Phnom Penh 120404, Cambodia

† Corresponding author: Bimastyaji Surya Ramadan; bimastyaji@live.undip.ac.id

ORCID IDs 0000-0002-5194-0743

Abstract: This study aims to develop a comprehensive inventory of air pollutants and GHG emissions from the waste sector for the 2024–2033 period and to formulate locally relevant mitigation strategies within the context of Indonesia's national climate mitigation framework. A mixed-method approach was applied, combining primary data from transect walk surveys across 12 representative wards with secondary datasets. Air pollutant emissions were estimated using the UNEP Atmospheric Brown Cloud (ABC) inventory method, while GHG emissions were quantified based on the IPCC (2006) Tier 2 methodology. Dispersion modeling using AERMOD was conducted to assess the contribution of waste-sector emissions to ambient air quality. Results indicate that the waste sector contributes 1.9%, 5.6%, and 1.6% to ambient concentrations of total particulate matter (TPM), NO_2, and SO_2, respectively. The GHG inventory identified Jatibarang Landfill and industrial wastewater as the dominant emission sources in the solid- and liquid-waste subsectors, respectively. The mitigation assessment indicates that methane capture at Jatibarang Landfill and the expansion of waste collection and 3R-based treatment facilities provide the greatest mitigation potential, while biodigester septic systems provide a comparatively smaller contribution because of their limited implementation coverage. These findings highlight the dominant role of landfill methane recovery and improved waste management infrastructure in emission mitigation. The proposed framework demonstrates a scalable, data-driven approach for cities to simultaneously address air pollution and climate change through integrated waste sector management.

Keywords: Air pollutants; Emission reduction strategy; Greenhouse gas inventory; Semarang City; Waste sector

1. INTRODUCTION

Urbanization and population growth in Indonesian metropolitan cities have increased pressure on municipal waste management systems, leading to higher emissions of air pollutants and greenhouse gases (GHGs) from inadequate waste treatment practices. Semarang City, the capital of Central Java Province, is one of the

cities facing this and non-methane volatile organic compounds (NMVOCs) (Astuti[1] & Rauf, 2024; Shrestha et al., 2013; Sukma, Kristanto, & Dahlan, 2025). Domestic wastewater management also remains limited, as up to 96.08% of households use septic tanks, while only about 7% are connected to regional wastewater treatment plants (Enebe, Chigor, Obileke, Lawal, & Enebe, 2023; Raman et al., 2024; Semarang, 2023). At the same time, wastewater loads generated from industrial zones continue to increase.

As a result, Semarang continues to face air quality challenges (Santosa, Okuda, & Tanaka, 2008). In the broader Indonesian urban context, air quality degradation is commonly associated with elevated Air Quality Index (AQI) levels and fine particulate matter ($PM_{2.5}$), which can exceed the World Health Organization (WHO) air quality guideline (WELL, 2024). Total GHG emissions in Semarang reached 5,281.97 Gg CO_2eq in 2022, with the waste sector contributing 28.37% of total emissions (Semarang, 2023). Open burning is an important source of black carbon (BC) and other short-lived climate pollutants (SLCPs), while landfill decomposition generates CH_4 and other gases such as hydrogen sulfide (H_2S) and ammonia (NH_3), which may pose environmental and health risks (Abdel-Shafy, Ibrahim, Al-Sulaiman, & Okasha, 2024; Abidin, Maziya, Susetyo, Yoneda, & Matsui, 2024; Coppola et al., 2022; Gangwar et al., 2019; Kannankai & Devipriya, 2024; Lott, Laux, & Townsend, 2024).

In Indonesia, several policy frameworks have been established to address these issues, including Government Regulation No. 22/2021 on Environmental Protection and Management, which regulates ambient air quality standards, and Presidential Regulation No. 98/2021 on Carbon Economic Value, which supports Indonesia's Nationally Determined Contribution (NDC) target of reducing GHG emissions by 29% against the business-as-usual (BAU) scenario by 2030. However, local emission data for Semarang remain limited, and existing emission inventories are often simplified because they rely on broader national or regional studies and default Intergovernmental Panel on Climate Change (IPCC) emission factors rather than localized activity data (Chaerul & Wardhani, 2020; B. S. Ramadan, Rachman, Ikhlas, et al., 2022). Moreover, previous studies on SLCPs from Semarang's waste management system have shown that uncontrolled waste handling and open burning are major sources of BC and CH_4 emissions, while also highlighting the mitigation potential of improved organic–inorganic waste separation and treatment technologies (B. S. Ramadan, Fajar, & Puspita, 2024).

Therefore, this study develops a detailed inventory of air pollutants and GHG emissions from the solid and liquid waste sectors in Semarang City using city-level reports and localized data (Budihardjo, Humaira, Ramadan, Wahyuningrum, & Huboyo, 2023; Budihardjo, Yuliastuti, & Ramadan, 2021; Nasional, 2023). The objectives are to quantify emissions from landfilling, open burning, composting, recycling, and domestic and industrial wastewater treatment, and to identify major emission sources requiring integrated GHG reduction strategies. The findings are expected to provide local evidence for prioritizing waste-sector mitigation measures and supporting monitoring efforts aligned with Indonesia's NDC target and national ambient air quality standards.

Indonesia's climate mitigation framework has continued to evolve following the submission of the Second Nationally Determined Contribution (Second NDC) in 2025. The Second NDC provides updated national emission pathways using 2019 as the reference year and presents projected emission levels for 2030 and 2035 under different development and mitigation scenarios. Therefore, national NDC targets should not be directly interpreted as uniform reduction requirements for individual cities or waste-sector inventories without an official sectoral or subnational allocation. In this study, the national NDC framework is used as a policy context rather than as a formally allocated emission-reduction target for Semarang City. Accordingly, the mitigation assessment focuses on quantifying the potential emission reductions achievable through locally relevant waste-management strategies and evaluating their contribution to Indonesia's broader climate mitigation objectives.

2. MATERIALS AND METHODS

2.1 Study Area and Data Collection

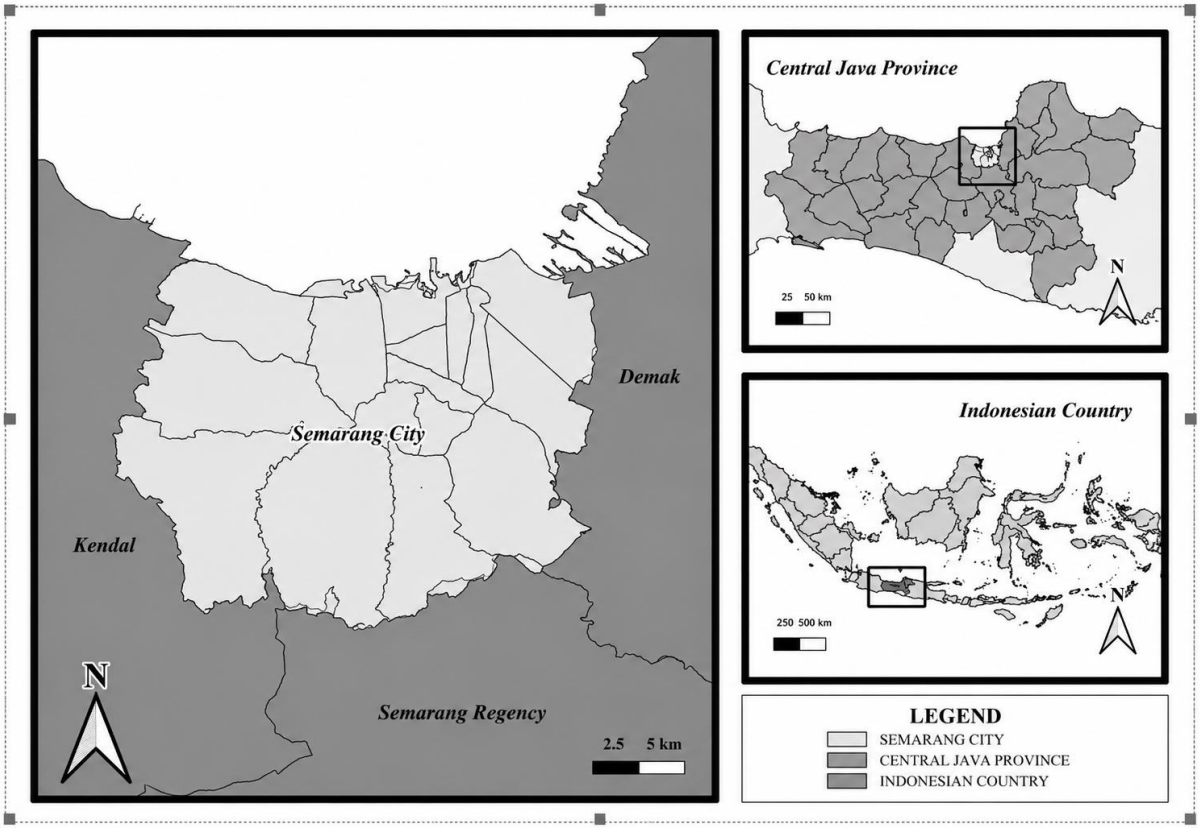


Fig 1. Study area

This study was conducted in Semarang City, Central Java, Indonesia (6°50'–7°10'S; 109°35'–110°50'E), with a coverage area of all 16 sub-districts and 177 urban wards (area of the city is 37,378 ha) during the planning period for years 2024–2033. Transect walk surveys were conducted for the collection of primary data on open burning waste characteristics (November 19 – December 5, 2024; 10 km/ward) in three cluster types (peri-urban/rural/city center) across twelve representative wards. Burning site dimensions, rate of burning,

waste density and distance from the observer were among the parameters that were measured. Waste was then collected, sorted and weighed by composition category. The 12 survey wards were distributed across three urban typologies of Semarang City: peri-urban, rural, and city-center areas. Within each selected ward, a 10-km transect walk was conducted to identify and characterize observable unmanaged-waste and open-burning locations. The observations were used to derive the proportion of unmanaged waste and the fraction of unmanaged waste subjected to open burning for each urban cluster. The citywide fractions were subsequently obtained by combining the cluster-level results across the surveyed wards and applying the resulting citywide fractions to the total municipal solid waste generation projected for Semarang City. The resulting citywide estimates were then used to estimate the quantity of openly burned waste across all 177 wards using ward-level population data. Secondary data were collected from Semarang Environmental Agency, BPS, SIPSN, and climate databases (Copernicus CDS, NASA Power). The characteristics of domestic wastewater in Semarang and methane emission factors from communal WWTPs were also incorporated into the inventory (Nuraeni & Ashuri, 2018; Sumiyati, Sutrisno, Sudarno, & Wicaksono, 2023).

2.2 Population and Waste Generation Projections

Population projections for 2024–2033 were estimated using a geometric growth model based on historical population data for Semarang City. The projected population was calculated using:

$$P_t = P_0(1 + r)^t$$

Where P_t is the projected population in year t, P_0 is the population in the baseline year, r is the annual population growth rate, and t is the number of years from the baseline year.

Municipal solid waste generation for 2024–2033 was projected using an urban-growth approach that incorporates population growth and socioeconomic indicators, including per-capita GRDP growth, agricultural-sector growth, and industrial-sector growth. The composite annual growth rate of waste generation (C_s) was calculated as:

$$C_s = \frac{1 + \frac{C_i + C_p + C_{qm}}{3}}{1 + P} - 1$$

Where C_s is the composite annual growth rate of waste generation, C_i is the annual industrial-sector growth rate, C_p is the annual per-capita GRDP growth rate, C_{qm} is the annual agricultural-sector growth rate, and P is the annual population growth rate. All growth rates were expressed as decimal fractions in the calculation.

Annual municipal solid waste generation was subsequently estimated using:

$$Q_n = Q_0(1 + C_s)^n$$

Where Q_n is the projected waste generation in year n (tons/year), Q_0 is the municipal solid waste generation in the baseline year (tons/year), C_s is the composite annual waste-generation growth rate, and n is the number of years from the baseline year. The 2023 municipal solid waste generation of 431,534.65 tons/year was used as the baseline. The calculation was applied sequentially for each year from 2024 to 2033 using the corresponding annual growth parameters.

Population and socioeconomic data, including population, per-capita GRDP, agricultural-sector growth, and industrial-sector growth, were obtained from Statistics Indonesia (BPS) and relevant Semarang City statistical publications. Municipal solid waste generation data were obtained from the Semarang City waste-management database. The input parameters used for the projections are summarized in Table 1.

Population projections (2024–2033) were made using geometric regression ($R^2 = 0.9931$), from 1,708,773 (2024) to 1,840,414 inhabitants (2033). Cases of waste generation were calculated with an urban growth model considering population, per capita GRDP (gross regional domestic product), agricultural and industrial sector growth rates resulting in estimated values ranging from 442,572 tons/year (2024) to 527,078 tons/year (2033) (Damanhuri & Padmi, 2019). The fraction of unmanaged waste (25.74%) and the open burning fraction (77.85 %) were obtained based on analysis of transect walk throughout all 177 wards.

2.3 Air Pollutant Inventory and Dispersion Modeling

For open burning, air pollutant (SO_2, NO_2, TPM) emission was calculated using the UNEP ABC method, with reported emission factor EF(SO_2) = 0.50 g/kg, EF(NO_2) = 3.18 g/kg and EF(TPM) = 0.48 g/kg dry waste burned (Nguyen et al., 2020; Okedere et al., 2019; B. S. Ramadan, Rachman, & Matsumoto, 2022; Wang et al., 2022). Additional emission factors from open burning studies in Semarang were also considered for validation (B. S. Ramadan, Rachman, & Matsumoto, 2022). For dispersion modeling, AERMOD View was used with meteorological preprocessing via AERMET View using two years of climate data (2022–2023) from Copernicus CDS and NASA Power. R and RMSE were applied to model validation. Load carrying capacity was considered by comparing the maximum modeled concentration with national standard (PP No. 22/2021): TPM 230 µg/m³, NO_2 200 µg/m³, SO_2 75 µg/m³ (24-hour average). Annual air pollutant emissions from open waste burning were calculated using Equation.

$$E_{i,y} = M_y \times EF_i \times 10^{-3}$$

where $E_{i,y}$ is the annual emission of pollutant i in year y (Gg/year), M_y is the mass of openly burned waste (Gg/year), EF_i is the pollutant-specific emission factor (g/kg waste), and 10^{-3} is the unit-conversion factor. The emission factors applied were 0.48 g/kg for TPM, 3.18 g/kg for NO_2, and 0.50 g/kg for SO_2. All calculations were performed using unrounded waste quantities, while the values reported in the tables were rounded to three decimal places.

2.4 Greenhouse Gas Inventory

GHG inventories were conducted according to the IPCC (2006) Tier 2 approach (IPCC, 2006). Landfill CH_4 emissions were estimated using a waste-type-specific first-order decay model, considering degradable organic carbon (DOC), the fraction of degradable organic carbon decomposed (DOCf), and the methane generation rate constant (k). Landfill gas emission characteristics from Jatibarang Landfill were used to refine the model (Abidin et al., 2024). Composting emissions were estimated using emission factors namely EF(CH_4) = 0.092 g/kg waste and EF(N_2O) = 0.42 g/kg waste (Lu, Li, & An, 2020). These emission factors were used as proxy values because site-specific CH_4 and N_2O emission factors for composting activities in Semarang are currently unavailable (Themelis & Bourtsalas, 2021). The waste characteristics and composting conditions in Baoding, China, are not assumed to be identical to those in Semarang; therefore, the use of these emission factors introduces uncertainty (Sumiyati et al., 2023). However, composting contributed only a minor share of total solid waste GHG emissions in this study. This assumption is not expected to change the identification of dominant emission sources, namely landfilling and open burning. Future studies should develop locally measured emission factors based on direct CH_4 and N_2O flux monitoring from composting facilities in Semarang.

2.5 Emission Reduction Strategy Development

The ammonium Strategies identified through literature review were assessed via sensitivity analysis. The first design strategy was methane capture by HDPE geomembrane on 7.73 ha (58% of remaining landfill area), using 12 extraction wells with a CH_4 recovery rate of 0.024 ton/ton waste, a consistent with recovery efficiencies reported for landfill gas recovery projects (Themelis & Bourtsalas, 2021). The second design would cover Biogas Utilization System Unit (BSU) expansion (81 new units/year; get to 80% coverage in each ward) and Temporary Waste Storage Facility (TWSF) has constructed per Semarang's Waste Master Plan for Waste Management in Semarang within the period of 2023–2042; and lastly biodigester septic tanks installations will be delivered to new residents build-in with replacing conventional septic tanks that have an average efficiency installing CH_4 capture of about 80%, based on over literature review methods like (Bhatt & Tao, 2020). The use of biodigesters for domestic wastewater treatment is also supported by local emission factor studies (Nuraeni & Ashuri, 2018). Drawing from integrated mitigation approaches in the agricultural sector, which combine biochar application, alternate wetting and drying (AWD) irrigation, and bio solar fuel substitution to achieve significant GHG and air pollutant reductions, this study adopts a multi-strategy framework for the waste sector (B. Ramadan et al., 2026). The mitigation strategies were evaluated based on their potential to reduce GHG emissions relative to the projected business-as-usual (BAU) scenario for Semarang City. The assessment considered the magnitude of emission reductions achieved by each strategy and the combined mitigation potential of the integrated scenario. The previous 29% reduction benchmark was initially considered as a reference to the former Indonesian NDC framework; however, it was not treated as an officially allocated target for the Semarang waste sector. In view of the updated Second NDC, the present analysis does not claim formal compliance with a

national NDC target. Instead, the mitigation results are interpreted as a city-level assessment of the potential contribution of waste-sector interventions to Indonesia's broader climate mitigation objectives.

3. RESULTS AND DISCUSSION

3.1. Projection of Municipal Solid Waste Generation in Semarang City

The basic source of inventory data for the solid waste subsector is waste generation, which can be used to quantify air pollutants and greenhouse gases (GHGs) emitted from this sector. Waste generation was projected using the composite growth approach described in Section 2.2. Waste Generation in Development Based on 2023 Baseline Data (BPS Kota Semarang, 2024; RAD GRK, 2023), waste generation in 2023 was recorded at 431.534,65 tons/year. In 2024 population increased from 1694740 to 1708773 (0.83% growth rate), Per Capita GDP increase IDR 91,190,000 to IDR 97,256,667 (6.65%), agricultural GDP increase from IDR billion to IDR billion (1.62%) and industrial GDP increase from IDR billion to IDR billion (3.25%).

The composite growth rate for waste (Cs) was calculated as:

$$Cs = \frac{1+\frac{Cs+Cp+Cqm}{3}}{1+P} - 1jadi$$

where Ci represents industrial growth, Cp denotes per capita GDP growth, Cqm refers to agricultural growth, and P indicates population growth. For the year 2024, the composite growth rate was estimated at Cs = 2.6%. Based on this value, the projected waste generation was calculated as follows:

$$Qn = Qt \times (1+Cs)n = 431,534.65 \times (1+0.026)1 = 442,572.47 \text{ tons/year}$$

This process was repeated for the years 2024–2033 as shown in Table 1. Waste evolution is expected to grow gradually, from 431,534.65 tons/yr in 2023 to 527,078.41 tons/yr in the year of 2033 (cumulative growth of around 22.1% over a decade). The increase is led mainly by per capita GDP growth (with average 1.59% yearly, industrial growth) and population growth is still modest (0.82-0.83% a year). The calculations ascribed waste to landfill, composting and open burning based on these projections in future emissions calculations.

Table 1. Projected Municipal Solid Waste Generation in Semarang City, 2024–2033

Year	Ci (%)	Cp (%)	Cqm (%)	P (%)	Cs (%)	Qn (tons/year)
2024	2.042	4.725	6.744	2.051	02.06	442,572.47
2025	3.147	1.590	6.238	0,570	02.05	453,143.97
2026	3.051	1.590	5.872	0,570	02.04	463,316.84
2027	2.961	1.590	5.546	0,570	02.03	473,146.78
2028	2.876	1.590	5.254	0,570	02.03	482,680.17

2029	2.796	1.590	4.992	0,570	02.02	491,956.00
2030	2.719	1.590	4.755	0,570	02.02	501,007.34
2031	2.647	1.590	4.539	0,570	02.01	509,862.47
2032	2.579	1.590	4.342	0,570	02.01	518,545.78
2033	2.514	1.590	4.161	0,570	02.00	527,078.41

3.2 Waste Generation Projection and Open Burning Quantification

In 2023, the baseline waste generation of Semarang City amounted to 431,534.65 tons/year. Using compound growth rate with population (0.83% year^{-1}), per capita GDP (6.65% year^{-1}), agricultural GDP (1.62% year^{-1}) and industrial GDP (3.25% year^{-1}), waste generation was predicted to increase from 273,557 tons/year in 2017 to 527,078.41 tons/year in 2033, as shown in Table 2. Waste grew at an average annual rate of 2.0–2.6%.

Table 2. Projected Waste Generation (tons/year) and Openly Burned Waste (Gg/year)

Year	Total MSW (tons/year)	Open burning waste (Gg/year)
2024	442,572	88.70
2025	453,144	90.82
2026	463,317	92.85
2027	473,147	94.82
2028	482,68	96.73
2029	491,956	98.59.00
2030	501,007	100.41.00
2031	509,862	102.18.00
2032	518,546	103.92
2033	527,078	105.63

The transect-walk survey across the 12 selected wards was used to characterize unmanaged waste and open-burning practices across the three urban typologies. The survey estimated that unmanaged waste represented 25.74% of total municipal solid waste (MSW). Among the unmanaged waste observed, 77.85% was estimated to be openly burned at the citywide level. Cluster-level open-burning fractions were 82.71% for peri-urban areas, 82.08% for rural areas, and 68.75% for city-center areas. These cluster-level results were combined to obtain the citywide estimate, which was subsequently applied to the projected municipal solid waste generation to estimate the annual quantity of openly burned waste. Accordingly, the estimated openly burned waste was 88.70 Gg in 2024 and increased to 105.63 Gg by 2033 under the BAU scenario. The highest open burning rates were in peri-urban (82.71%) and rural (82.08%) clusters, whereas it's the lowest was for city-center (68.75%). Thus, the amount of waste incinerated in open conditions increased from 88.70 Gg in 2024 to 105.63 Gg within the business-as-usual (BAU) scenario until 2033.

Because the primary survey covered 12 wards rather than the entire 177-ward population, the citywide estimate is subject to sampling and spatial representativeness uncertainty. A formal statistical confidence interval could not be calculated because the available survey results did not include sufficient ward-level replicate data for variance estimation. Therefore, a cluster-based sensitivity assessment was conducted using the observed open-burning fractions across the three urban typologies (68.75–82.71%). Holding the estimated unmanaged-waste fraction constant at 25.74%, the corresponding 2024 openly burned waste ranged from approximately 78.32 to 94.22 Gg/year, compared with the central estimate of 88.70 Gg/year. This range represents approximately −11.7% to +6.2% variation around the central estimate and indicates the uncertainty associated with extrapolating the survey results to the citywide scale.

3.3 Open Burning Emissions of Air Pollutants

Open burning of unmanaged waste was modeled as an area source aggregated from 177 villages. Per capita open burning was 0.010976 tons/person/year (1.65×10^{-6} kg/person/s) in Semarang. Using these rates and village level population data, the open burning waste mass for each village was estimated. Calculations of emissions of TPM, NO_2 and SO_2 were made using emission factors from Shrestha et al. 2013: 0.48 g TPM/kg waste; 3.18 g NO_2/kg waste; and 0.50 g SO_2/kg waste Emissions from the example can be seen for Cepoko village (total population 3,441): TPM-0.00272 g/s, NO_2– 0.01801 g/s, SO_2– 0.00283 g/s. Among the three pollutants, NO_2 exhibited the highest emission load because the NO_2 emission factor used in the inventory (3.18 g/kg) was substantially higher than those used for TPM (0.48 g/kg) and SO_2 (0.50 g/kg).

Based on the projected amount of openly burned waste and the stated emission factors, NO_2 emissions are estimated to increase from 0.282 Gg/year in 2024 to 0.336 Gg/year in 2033. Over the same period, TPM emissions increase from approximately 0.043 to 0.051 Gg/year, while SO_2 emissions increase from approximately 0.044 to 0.053 Gg/year. The higher NO_2 emission load reflects its larger emission factor of 3.18 g/kg compared with 0.48 g/kg for TPM and 0.50 g/kg for SO_2. These values are in accordance with historically documented inventories for Semarang (B. S. Ramadan, Rachman, & Matsumoto, 2022).

Table 3. Annual Air Pollutant Emissions from Open Burning in Semarang City (2024–2033)

Year	Open burning waste (Gg/year)	TPM (Gg/year)	NO_2 (Gg/year)	SO_2 (Gg/year)
2024	88.70	0.043	**0.282**	0.044
2025	90.82	0.044	**0.289**	0.045
2026	92.85	0.045	**0.295**	0.046
2027	94.82	0.046	**0.302**	0.047
2028	96.73	0.046	**0.308**	0.048
2029	98.59	0.047	**0.314**	0.049
2030	100.41	0.048	**0.319**	0.050
2031	102.18	0.049	**0.325**	0.051
2032	103.92	0.050	**0.330**	0.052
2033	105.63	0.051	**0.336**	0.053

*Emission factors: TPM = 0.48 g/kg, NO_2 = 3.18 g/kg, SO_2 = 0.50 g/kg

3.4 GHG Inventory – Liquid Waste Subsector

Emissions from liquid wastes were assessed for domestic (communal, septic tanks, IPLT sludge treatment plant, N_2O emitted via effluent discharged) and three industrial sources (steel, organic chemicals, flour processing). Since domestic methane from communal WWTPs was very low (0.0048–0.0052 Gg CH_4/year) because just 8.57% population coverage, redundancy of centralized systems would probably be lower than the randomized configurations in their respective assortments. Performance of Domestic Emissions Data until October 2023Septic tanks were the dominant contributor with their emissions from507.7Gg CH_4/year during last decade which increased to2462.6 (0.211–0.227Gg CH_4/year) over2024–2033, equivalent to a 91.26% coverage, as presented in Table 4. The second stage of the IPC also added CH_4 to total emissions: IPLT contributed 0.0735–0.0792 Gg CH_4/year The estimated annual direct N_2O emissions from domestic effluent ranged from 0.0525 to 0.0565 Gg N_2O/year, which expanded the uncertainty of the conventional risk assessment because there were limited data availability of emission factors used in this study.

Among the industrial sources, the flour processing industry generated 4,585 kg CH_4/year (constant) by discharge of wastewater containing a precipitation waste factor of 9 m^3/ton product and COD load amounting to 18.5 kg/m^3. This study also indicated rising emissions in the organic chemicals industry (3,222 to 3,308 kg CH_4/year) and zero values for steel (36.5 kg CH_4/year). Industrial CH_4 emissions increased from 7,844 to 7,930 kg CH_4/year. The total GHG emissions from the liquid waste subsector (expressed in CO_2eq, using GWP CH_4 = 28, N_2O = 265) were estimated to be of about 187.05 Gg CO_2eq/year for 2024 (year base year of the projection period) and approximately approximately190.59 Gg CO_2eq/year for2033 Of the total, 88 percent of subsector emissions came from industrial wastewater.

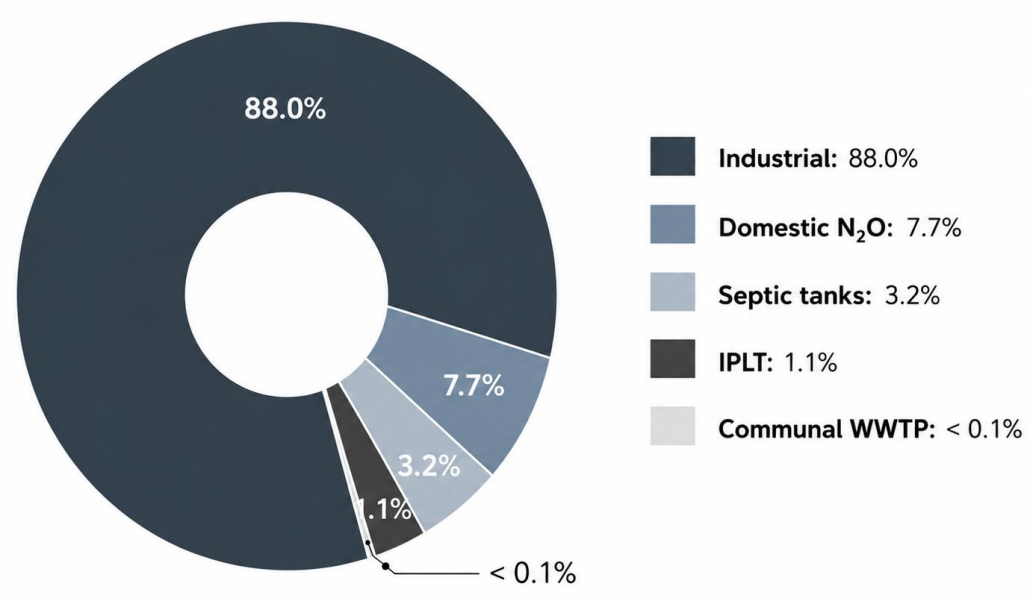


Fig 2. Contribution of different liquid waste sources to total GHG emissions in Semarang City (2024)

This dominance emphasizes that it also needs GHG policies for industry, in addition to those at the municipal level. Table 4 summarizes the components.

GHG emissions were converted to CO_2-equivalent using the global warming potential (GWP) values of 28 for CH_4 and 265 for N_2O. For each emission source, CH_4 and N_2O quantities were first calculated in Gg and subsequently converted to Gg CO_2eq by multiplying the respective gas mass by its GWP. The total GHG emissions were then obtained by summing the CO_2-equivalent contributions from all relevant sources.

Table 4. GHG Emissions from Liquid Waste Subsector (Gg CO_2eq/year)

Source	2024	2033	Share (%)
Communal WWTP (CH_4)	0.14	0.15	<0.1
Septic tanks (CH_4)	5.91	6.36	3.16
IPLT (CH_4)	2.06	2.22	1.01
Domestic N_2O	13.91	14.97	7.44
Industrial (CH_4)	165.03	166.90	88.23
Total	187.05	190.60	100

3.5 GHG Inventory – Solid Waste Subsector

Jatibarang landfill was responsible for most emissions from solid waste in Semarang City: Methane emissions at ladfill peaked at 13.10 (Gg CH_4/year) in 2022 after methane recovery stopped, followed by decline to stabilize projected to be at 10.52 Gg by2033 (Figure 3).

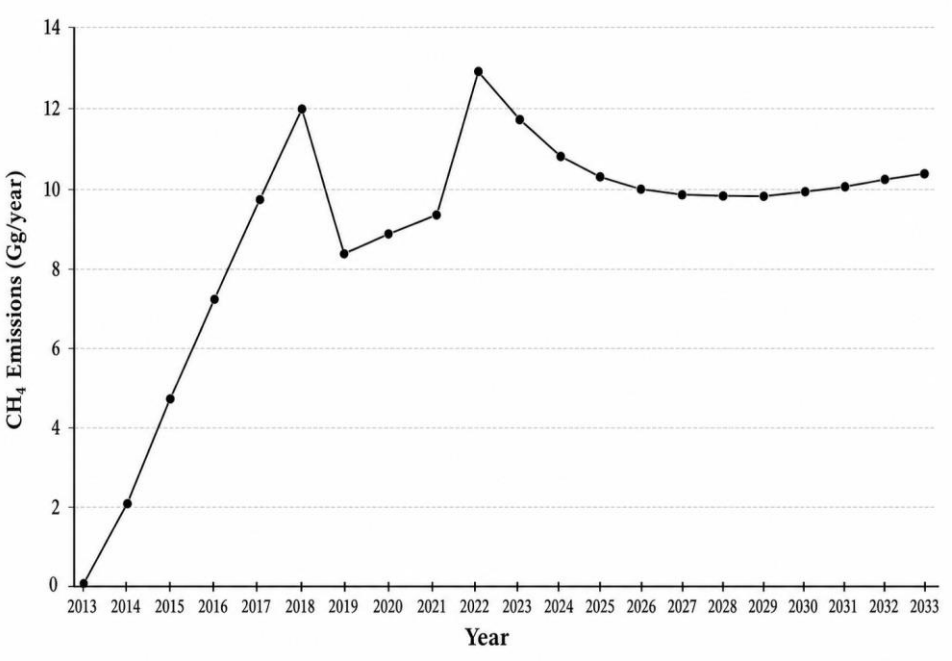


Fig 3. Methane emissions from Jatibarang landfill in Semarang City (2013–2033)

The second-largest source of solid-waste GHG emissions was open burning. Emissions from open burning increased from approximately 102.05 Gg CO_2eq/year in 2024 to 122.01 Gg CO_2eq/year in 2033. Composting contributed only a minor share of total solid-waste emissions, increasing from approximately 1.09 Gg CO_2eq/year in 2024 to 2.02 Gg CO_2eq/year in 2033. Overall, total GHG emissions from the solid-waste subsector increased from 409.14 Gg CO_2eq/year in 2024 to 418.59 Gg CO_2eq/year in 2033. Jatibarang Landfill remained the dominant emission source, followed by open burning, whereas composting contributed less than 1% of the total solid-waste GHG emissions.

Table 5. Solid Waste GHG Emissions (Gg CO_2eq/year)

Source	2024	2033	Share (%)
Jatibarang landfill (CH_4)	306.00	294.56	74.79
Open burning (CO_2+CH_4+N_2O)	102.05	122.01	24.94
Composting (CH_4+N_2O)	1.09	2.02	0.27

Total	409.14	418.59	100

3.6 Air Pollutant Dispersion Modeling (AERMOD)

AERMET View was applied to process meteorological data (2022–2023) obtained from Copernicus CDS and NASA Power. The wind rose plot indicated that the prevailing winds mostly blew from northwest to southeast direction (toward Banyumanik District) with calm wind condition (1.06%). The emission data of TPM, NO_2 and SO_2 due to open burning from 177 villages are entered in AERMOD View with a domain size of 30 km×25 km having 529 receptors. Model performance was evaluated by comparing the modeled concentrations with ambient monitoring data for 2023 and 2024 using equivalent averaging periods. Based on the corrected results presented in Table 5, the correlation coefficients ranged from 0.666 to 1.000, while the RMSE values ranged from 0.178 to 3.09 µg/m³. These results indicate variable model performance among pollutants and assessment years; therefore, the model should not be described uniformly as demonstrating strong correlations for all pollutants. Details of the monitoring locations, number of paired observations, data sources, and averaging periods are provided in Section 2.3.

Table 5. Statistical Evaluation of AERMOD Performance against Ambient Monitoring Data

Pollutant	**R (2023)**	**RMSE (2023), µg/m³**	**R (2024)**	**RMSE (2024), µg/m³**
TPM	0.670	0.178	0.670	3.09
SO_2	1.000	1.13	0.670	3.09
NO_2	0.666	1.39	0.690	0.85

Predicted maximum concentrations due to the waste sector alone were: TPM 0·793 µg/m³, NO_2 4·40 µg/m³, and SO_2 0·808 µg/m³ (2024), all well below national ambient standards. Nevertheless, when the background was considered — that is, after accounting for contributions from other sectors (transport, energy etc.) — total NO_2 concentration breached the 65 µg/m³ threshold in 2028 (146.6 µg/m³), and achieved absolute levels as high as 1,037 µg/m³ by 2033 due to strong sustained growth in non - waste NO_2 emissions (+48.7% per annum). Ambient concentrations (% total) sourced from the waste sector for all pollutants exhibited a dismal share with TPM 1.90% (g), NO_2 5.62% (h) and SO_2 1.60% (i) respectively, showing graphically a predicted dispersion for NO_2 in 2028 (Figure 5). Kemijen Ward (East Semarang) consistently exhibited the highest concentration for TPM and SO_2, whereas Sendangguwo Ward (Tembalang) has the highest NO_2 from waste-sector emissions.

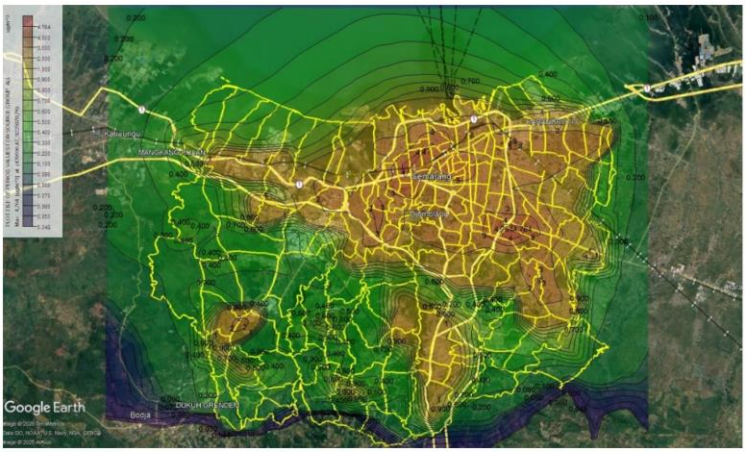


Figure 4. Dispersion pattern of NO_2 concentration in Semarang City (2028)

3.7 Emission Reduction Strategies and Outcomes

The mitigation assessment used the projected BAU scenario as the reference for evaluating the effectiveness of the proposed strategies, while the national NDC framework was considered a broader policy context rather than an officially allocated mitigation target for the Semarang waste sector. For 2030, the projected BAU emissions of 505.64 Gg CO_2eq/year were established as the baseline for calculating the mitigation outcome. Under the integrated mitigation scenario, emissions were projected to decrease to 356.78 Gg CO_2eq/year. For the solid-waste subsector, which was responsible for approximately 63% of total waste-sector GHG emissions, two principal strategies were evaluated: (1) methane capture at Jatibarang Landfill and (2) the expansion of waste-collection and treatment services through additional Waste Bank Units (BSUs) and 3R-based Waste Processing Facilities to reduce open waste burning. Methane capture across 7.73 ha, representing 58% of the remaining landfill area, was estimated to recover 4.14 Gg CH_4/year, reducing landfill GHG emissions by 35.15% (74.59 Gg CO_2eq) in 2030. Meanwhile, expanding BSUs and 3R-based Waste Processing Facilities to cover 80% of the RW (neighborhood units) was projected to reduce the amount of unmanaged waste subjected to open burning, resulting in a 76.79% reduction in open-burning emissions (79.68 Gg CO_2eq) by 2030. In the liquid-waste subsector, biodigester septic tanks were projected to be installed in 7,700 new households (717 units/year). However, this intervention reduced liquid-waste GHG emissions by only 0.09% because of its limited implementation coverage. Based on the 2030 BAU baseline, the integrated mitigation scenario produced an absolute reduction of 148.86 Gg CO_2eq/year, equivalent to a 29.44% reduction, decreasing emissions from 505.64 to 356.78 Gg CO_2eq/year in 2030, as shown in Table 6. Hence, the proposed strategies demonstrate substantial potential to contribute to Indonesia's broader climate mitigation objectives if implemented at the city level.

Table 6. Total GHG Emissions Before and After Reduction Strategies (Gg CO_2eq/year)

Year	BAU emissions	After mitigation	Reduction (%)
2024	508.44	508.44	0.00
2025	500.03	416.31	16.74

2026	496.53	412.82	16.86
2027	496.27	412.57	16.87
2028	498.15	414.47	16.80
2029	501.44	417.77	16.69
2030	505.64	356.78	**29.44**
2031	510.42	360.80	29.31
2032	515.58	365.05	29.20
2033	520.98	369.64	29.05

4. CONCLUSIONS

This study assessed air pollutant and greenhouse gas (GHG) emissions from the solid- and liquid-waste sectors in Semarang City for the 2024–2033 period and evaluated locally relevant emission-reduction strategies within the context of Indonesia's national climate mitigation framework. Open waste burning was estimated to emit approximately 0.051 Gg/year of TPM, 0.336 Gg/year of NO_2, and 0.053 Gg/year of SO_2 by 2033. The GHG inventory identified Jatibarang Landfill as the dominant source in the solid-waste subsector, contributing 294.56 Gg CO_2eq/year in 2033, followed by open burning at 122.01 Gg CO_2eq/year, while composting contributed 2.02 Gg CO_2eq/year. In the liquid-waste subsector, industrial wastewater remained the dominant source, contributing 166.90 Gg CO_2eq/year in 2033. Among the evaluated mitigation measures, methane capture at Jatibarang Landfill and improved waste collection and treatment through waste bank units and 3R-based facilities provided the greatest mitigation potential, whereas biodigester septic systems provided a comparatively smaller contribution because of their limited implementation coverage. These findings provide a city-level evidence base for prioritizing waste-sector mitigation measures in Semarang. The estimated mitigation potential should be interpreted as the contribution of the proposed local interventions to broader climate mitigation efforts rather than as evidence of formal compliance with an officially allocated national NDC target.

Author Contributions: Conceptualization, B.S.R and N.H.; methodology, B.S.R.; software, N.H.; validation, D.I.R.; formal analysis, A.S.; Y.M.; writing original article.

Funding: his research was funded by the Directorate of Research, Universitas Diponegoro, under the Collaborative Research Scheme (International Research Network/IRN), supported by the Indonesian Endowment Fund for Education (Lembaga Pengelola Dana Pendidikan/LPDP) through the Higher Education Endowment Fund (Dana Abadi Perguruan Tinggi/DAPT) for the 2025–2026 fiscal year, under Assignment Letter No. 869-37/UN7.D2/PP/XII/2025.

Institutional Review Board Statement: Not applicable. This study did not involve humans or animals.

Informed Consent Statement: Not applicable. This study did not involve humans or animals.

Acknowledgments: The authors would like to express their sincere appreciation to Bariq Andika Putra and Muhammad Satria Rachman for their valuable assistance with data collection.

Conflicts of Interest: Not applicable. This study did not involve human participants.

REFERENCES

Abdel-Shafy, H. I., Ibrahim, A. M., Al-Sulaiman, A. M., & Okasha, R. A. (2024). Landfill leachate: Sources, nature, organic composition, and treatment: An environmental overview. *Ain Shams Engineering Journal, 15*(1), 102293.

Abidin, A. U., Maziya, F. B., Susetyo, S. H., Yoneda, M., & Matsui, Y. (2024). Heavy metal air pollution in an Indonesian landfill site: Characterization, sources, and health risk assessment for informal workers. *Environmental Advances, 15*, 100512.

Astuti[1], R. D. P., & Rauf, A. U. (2024). Outdoor air pollution due to transportation, landfill, and. *Health and Environmental Effects of Ambient Air Pollution: Volume 1: Air Pollution, Human Health, and the Environment*, 257.

Bhatt, A. H., & Tao, L. (2020). Economic perspectives of biogas production via anaerobic digestion. *Bioengineering, 7*(3), 74.

Budihardjo, M. A., Humaira, N. G., Ramadan, B. S., Wahyuningrum, I. F. S., & Huboyo, H. S. (2023). Strategies to reduce greenhouse gas emissions from municipal solid waste management in Indonesia: The case of Semarang City. *Alexandria Engineering Journal, 69*, 771-783.

Budihardjo, M. A., Yuliastuti, N., & Ramadan, B. S. (2021). Assessment of greenhouse gases emission from integrated solid waste management in semarang city, central java, indonesia.

Chaerul, M., & Wardhani, A. K. (2020). Refuse Derived Fuel (RDF) dari Sampah Perkotaan dengan Proses Biodrying: Review. *2020, 17*(1), 13. doi:10.14710/presipitasi.v17i1.62-74

Coppola, A. I., Wagner, S., Lennartz, S. T., Seidel, M., Ward, N. D., Dittmar, T., . . . Jones, M. W. (2022). The black carbon cycle and its role in the Earth system. *Nature Reviews Earth & Environment, 3*(8), 516-532.

Damanhuri, E., & Padmi, T. (2019). *Pengelolaan sampah terpadu*: Itb Press.

Enebe, N. L., Chigor, C. B., Obileke, K., Lawal, M. S., & Enebe, M. C. (2023). Biogas and syngas production from sewage sludge: a sustainable source of energy generation. *Methane, 2*(2), 192-217.

Gangwar, C., Choudhari, R., Chauhan, A., Kumar, A., Singh, A., & Tripathi, A. (2019). Assessment of air pollution caused by illegal e-waste burning to evaluate the human health risk. *Environment international, 125*, 191-199.

IPCC. (2006). Guidelines for national greenhouse gas inventories. *Prepared by the National Greenhouse Gas Inventories Programme. Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K, editors. Published: IGES, Japan*.

Kannankai, M. P., & Devipriya, S. P. (2024). Atmospheric microplastic deposition in a coastal city of India: The influence of a landfill source on monsoon winds. *Science of the Total Environment, 908*, 168235.

Lott, D. J., Laux, S. J., & Townsend, T. G. (2024). Analysis of ammonia-nitrogen removal kinetics by stage in pilot scale vertical flow wetlands treating landfill leachate in series. *Chemosphere, 360*, 142409.

Lu, C., Li, W., & An, C. (2020). The GHG emission determinants research for waste disposal process at city-scale in Baoding. *Sustainable Cities and Society, 59*, 102203.

Nasional, S. I. P. S. (2023). *Waste Generation Data Semarang City 2023*.

Nguyen, T. K. O., Lai, N. H., Permadi, D. A., Nguyen, N. H. C., Sothea, K., Chitaporpan, S., . . . Sichum, S. (2020). Emission inventories for air pollutants and greenhouse gases with emphasis on data management in the cloud. *TORUS 3–Toward an Open Resource Using Services: Cloud Computing for Environmental Data*, 41-71.

Nugroho, R. A., Rofiq, M. N., Santoso, A. D., Yanuar, A. I., Hanifa, R., & Nadirah, N. (2023). Bioconversion of biowaste by black soldier fly larvae (Hermetia illucens L.) for dried larvae production: A life cycle assessment and environmental impact analysis. *F1000Research, 12*, 814.

Nuraeni, R., & Ashuri, A. (2018). Wastewater Specific Emission Factor From Communal Wastewater Treatment Plant (WWTP). *Widyariset, 4*(1), 37-48.

Okedere, O. B., Olalekan, A. P., Fakinle, B. S., Elehinafe, F. B., Odunlami, O., & Sonibare, J. (2019). Urban air pollution from the open burning of municipal solid waste. *Environmental Quality Management, 28*(4), 67-74.

Ramadan, B., Istirokhatun, T., Priguna, K., Azhari, N., Puspita, A., Samadikun, B., & Balasbaneh, A. T. (2026). Greenhouse Gas and Air Pollutant Mitigation Strategies for Sustainable Agriculture in Grobogan District, Indonesia. *International Journal of Sustainable Development and Planning, 21*(1), 61-70.

Ramadan, B. S., Fajar, I., & Puspita, A. S. (2024). Estimating short-lived climate pollutions emission from waste management system in Semarang–a life cycle and material flow analysis. *Ecological Engineering & Environmental Technology, 25*.

Ramadan, B. S., Rachman, I., Ikhlas, N., Kurniawan, S. B., Miftahadi, M. F., & Matsumoto, T. (2022). A comprehensive review of domestic-open waste burning: recent trends, methodology comparison, and factors assessment. *Journal of Material Cycles and Waste Management, 24*(5), 1633-1647.

Ramadan, B. S., Rachman, I., & Matsumoto, T. (2022). Activity and emission inventory of open waste burning at the household level in developing countries: a case study of Semarang City. *Journal of Material Cycles and Waste Management, 24*(3), 1194-1204.

Raman, A. P. S., Aslam, M., Singh, P., Pandey, G., Jain, P., & Kumari, K. (2024). Solid and liquid waste management in urban and rural areas: current practices and future perspectives *Integrated Waste Management: A Sustainable Approach from Waste to Wealth* (pp. 141-157): Springer.

Santosa, S. J., Okuda, T., & Tanaka, S. (2008). Air pollution and urban air quality management in Indonesia. *CLEAN–Soil, Air, Water, 36*(5-6), 466-475.

Semarang, D. L. H. K. (2023). *Rencana Aksi Daerah Gas Rumah Kaca (RAD GRK) Kota Semarang*. Semarang, Jawa Tengah: Dinas Lingkungan Hidup Kota Semarang.

Shrestha, R. M., Kim Oanh, N., Shrestha, R., Rupakheti, M., Rajbhandari, S., Permadi, D., . . . Iyngararasan, M. (2013). Atmospheric brown clouds: Emission inventory manual. *United Nations Environment Programme*.

Sukabudhi, R. M. I., Indrasti, N. S., & Ismayana, A. (2025). STUDY OF GLOBAL WARMING POTENTIAL IMPACT FROM MUNICIPAL SOLID WASTE MANAGEMENT USING BIOCONVERSION OF BLACK SOLDIER FLY (Hermetia illucens): CASE STUDY DEPOK CITY. *Jurnal Teknologi Industri Pertanian, 35*(1), 44-44.

Sukma, B., Kristanto, G. A., & Dahlan, A. V. (2025). Landfill design based on methane gas emission estimates at jatibarang final disposal site (TPA) in Semarang city using LandGEM 3.03 and its potential utilization as an energy source. *Indonesian Journal of Multidisciplinary Science, 4*(5), 310-328.

Sumiyati, S., Sutrisno, E., Sudarno, S., & Wicaksono, F. (2023). Domestic wastewater treatment using hybrid biofilm bioreactor–phytoremediation technology. *2023, 21*(2), 5. doi:10.14710/jil.21.2.403-407

Themelis, N. J., & Bourtsalas, A. (2021). Methane generation and capture of US landfills. *J. Environ. Sci. Eng. A, 10*(Apr), 199-206.

Wang, L., Du, W., Yun, X., Chen, Y., Zhu, X., Shen, H., . . . Tao, S. (2022). On-site measured emission factors of polycyclic aromatic hydrocarbons for different types of marine vessels. *Environmental Pollution, 297*, 118782.

WELL, I. (2024). International WELL Building Institute: Retrieved.

Yohana, E., Priyambada, I. B., Budihardjo, M. A., Puspita, A. S., & Haumahu, S. A. Q. (2026). Harnessing black soldier flies for eco-friendly food waste treatment: A case study from Semarang city. *Ecological Engineering & Environmental Technology (EEET), 27*(1), 35.