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Comparing Greenhouse Gas Emissions from Municipal Solid Waste Across Municipality Types in Thailand: A Province-Scale Study

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Thailand is among the countries most vulnerable to climate change, ranked 8th by the Global Climate Risk Index (CRI) for the period 1999–2018. In response, the National Strategy 2018–2037 outlines pathways for both adaptation and mitigation. The waste management sector is a notable contributor to greenhouse gas (GHG) emissions, accounting for more than 16,000 Gg CO₂-eq, approximately 4–5% of Thailand's total emissions. Municipal solid waste (MSW) management is particularly relevant in developing countries, where emissions vary considerably across municipality types. This study aims to determine GHG emissions from MSW management in Phitsanulok Province, Thailand, using questionnaire-based data collected from municipalities. Emissions were calculated for both end-of-life treatment and transportation stages. The results reveal significant differences across municipality types. City municipality generated the highest average emissions (26,531 tonnes CO₂-eq/year), followed by town municipality (4206 tonnes CO₂-eq/year), subdistrict municipality (1837 tonnes CO₂-eq/year), and subdistrict administrative organization (1168 tonnes CO₂-eq/year). While total emissions were greatest in the city municipality, per capita emissions did not scale proportionally, reflecting differences in population density, waste generation, and management practices. This province-scale analysis provides new insights into the role of municipality type in shaping waste-related emissions. The findings underscore the importance of differentiated climate mitigation strategies in the waste sector to develop more sustainable, low-carbon MSW management systems in Thailand and other developing countries.

Keywords: carbon emissions, landfill, solid waste, waste composition.

Introduction

Climate change is a major global threat, intensifying environmental risks and disrupting societies worldwide. Human-induced increases in greenhouse gas (GHG) concentrations have been linked to a rise in the frequency and severity of extreme weather events, including tropical cyclones, floods, droughts, wildfires, and heatwaves. According to the Emergency Events Database (EM-DAT) of the Centre for Research on the Epidemiology of Disasters (CRED), the number of recorded natural disasters has risen sharply since the 1980s, reaching 410 events in 2023 (Ritchie and Rosado, 2024). These disasters have profound consequences, resulting in loss of human and animal lives, damage to ecosystems, and significant social and economic costs. For example, the Arctic experienced its second-highest air temperatures and second-lowest sea ice extent on record in 2020 (UN, 2021), while an unprecedented cold wave in Texas the same year disrupted energy systems and caused widespread damage. More recently, Typhoon Ragasa, the most powerful tropical cyclone of 2025, killed at least 17 people in Taiwan and brought destructive winds and heavy rainfall to Hong Kong and China (Miller, 2025).

Climate change is driven by rising global temperatures, primarily caused by anthropogenic GHG emissions. Total human-induced GHG emissions have continued to increase, reaching 59 gigatonnes carbon dioxide equivalent (CO₂-eq) in 2019, about 54% (21 gigatonnes CO₂-eq) higher than 1990 levels (IPCC, 2022). The major sources of these emissions are the power industry, industrial combustion and processes, buildings, transportation, fuel exploitation, agriculture, and waste (EU, 2024). The waste sector is the seventh-largest contributor to global GHG emissions, accounting for approximately 5% of the total (EU, 2024; Oo et al., 2024). Notably, GHG emissions from the waste sector in 2023 were 56% higher than in 1990, highlighting the increasing importance of sustainable waste management in climate mitigation (EU, 2024).

In the waste sector, GHG emissions in developed countries have generally declined, according to global inventories (EU, 2024). For example, between 1990 and 2023, the United States reduced waste-related GHG emissions by 38%, the United Kingdom by 82%, and Germany by 73%. In contrast, emissions in developing

countries have risen sharply over the same period. China recorded a 212% increase, while Cambodia, the Philippines, Vietnam, and Thailand reported increases of 157%, 91%, 224%, and 156%, respectively. These rising emissions are largely attributable to landfilling and mismanagement practices such as open dumping and open burning (Oo et al., 2024).

In Thailand, the waste sector is the fourth-largest source of GHG emissions, contributing approximately 17,000 Gg CO₂-eq/year, or about 5% of the national total (MONRE, 2020). To address waste management and environmental sustainability, Thailand has implemented several strategic plans and policies. The Nationally Determined Contributions (NDC) were developed based on multiple roadmaps, including the first National Action Plan on Waste Management (2016–2021), which emphasized waste-to-energy technologies and the 3Rs (Reduce, Reuse, and Recycle) principle. In addition, the Pollution Control Department (PCD), in collaboration with other authorities, formulated the NDC Sectoral Action Plan for the Waste Sector (2021–2030), which targets a reduction of 2.0 megatonnes CO₂-eq from municipal solid waste (MSW) and municipal/industrial wastewater (Thailand Taxonomy Board, 2025). Despite these efforts, limited resources, inadequate capacity, and the lack of appropriate technologies at subnational and local levels remain major barriers to improving waste management systems (MONRE, 2020).

Currently, Thailand continues to face persistent GHG emissions from waste management challenges, particularly within local administrative organizations and municipalities. However, there remains limited empirical evidence on how GHG emissions from MSW differ across municipality types, especially at the provincial scale. Previous studies have largely focused on national inventories, single-case municipalities, or aggregated provincial and country-level data, without examining variations across local government structures or addressing the methodological implications of biogenic carbon (i.e., organic waste) accounting (MONRE, 2020; PCD, 2024; Saiphet and Kunta, 2023; Menikpura et al., 2012). For example, Saiphet and Kunta (2023) analyzed eight municipalities across different provinces to evaluate GHG emissions from food waste management, finding that urban and tourist city municipalities generate not only larger quantities of food waste but also higher food waste per capita compared to peri-urban

municipalities (Saiphet and Kunta, 2023). Similar patterns have been observed in other studies. Jawjit et al. (2025) assessed MSW-related GHG emissions in Nakhon Si Thammarat Municipality, a city municipality in southern Thailand, and identified organic waste fractions, particularly food and garden waste, as the dominant emission sources. This finding is further supported by Phonphoton and Tongsuntud (2026) in the Bangkok metropolitan area, confirming the significant contribution of biodegradable waste to overall emissions. At the municipal level, Outapa and Na Roi-et (2018) estimated total emissions of approximately 21,000 tonnes CO₂-eq/year in Lampang Municipality in northern Thailand, with disposal processes contributing more substantially than collection and transportation stages (Outapa and Na Roi-et, 2018; Rotthong et al., 2023). A similar pattern was reported by Lertyingcharoenchai et al. (2019), who found that approximately 98% of total emissions originated from disposal, compared to only 2% from collection and transportation. Despite these contributions, existing studies predominantly focus on individual municipalities or selected case studies, offering only fragmented insights at sub-provincial or provincial levels. In contrast, national datasets remain highly aggregated. The Pollution Control Department reports MSW generation at the provincial level, while the Ministry of Natural Resources and Environment provides GHG emission estimates only at the national scale (MONRE, 2020; PCD, 2024). This discrepancy in spatial resolution highlights a critical gap between localized empirical studies and national inventories, underscoring the need for integrated, province-level analyses at the municipal scale to capture intra-provincial variability in waste management practices and associated emissions.

To address this gap, the present study provides a novel province-level assessment that integrates municipal-scale, bottom-up data across different municipality types within a unified analytical framework. This approach enables a more detailed comparison of emissions across administrative structures and offers new insights into spatial heterogeneity that have not been captured in previous studies. In this context, Phitsanulok Province was selected as the case study owing to its diverse range of municipal classifications, including city municipalities, town municipalities, sub-district municipalities, and subdistrict administrative organizations. City municipalities typically represent

highly urbanized areas with greater population density and service capacity, whereas town and subdistrict municipalities cover progressively smaller and less densely populated areas. Subdistrict administrative organizations are primarily responsible for rural areas with more limited waste management infrastructure. These municipality types differ in terms of administrative responsibilities, population density, service coverage, and waste management capacity, which in turn influence waste generation rates and management practices (Saiphet and Kunta, 2023). Primary data was obtained directly from municipalities through structured questionnaire surveys, ensuring that the analysis reflects actual operational practices. The assessment used a life cycle assessment (LCA) framework to estimate emissions from both end-of-life treatment and transportation. Results are reported as emissions per municipality per year and per capita per year. To our knowledge, this is one of the first province-level studies in Thailand to quantify MSW-related GHG emissions by municipality type using bottom-up data. The results offer valuable insights for local governments and policymakers to develop more targeted, differentiated climate mitigation strategies in the waste sector, thereby supporting the transition toward sustainable, low-carbon municipal waste management systems.

Methods

Case study description

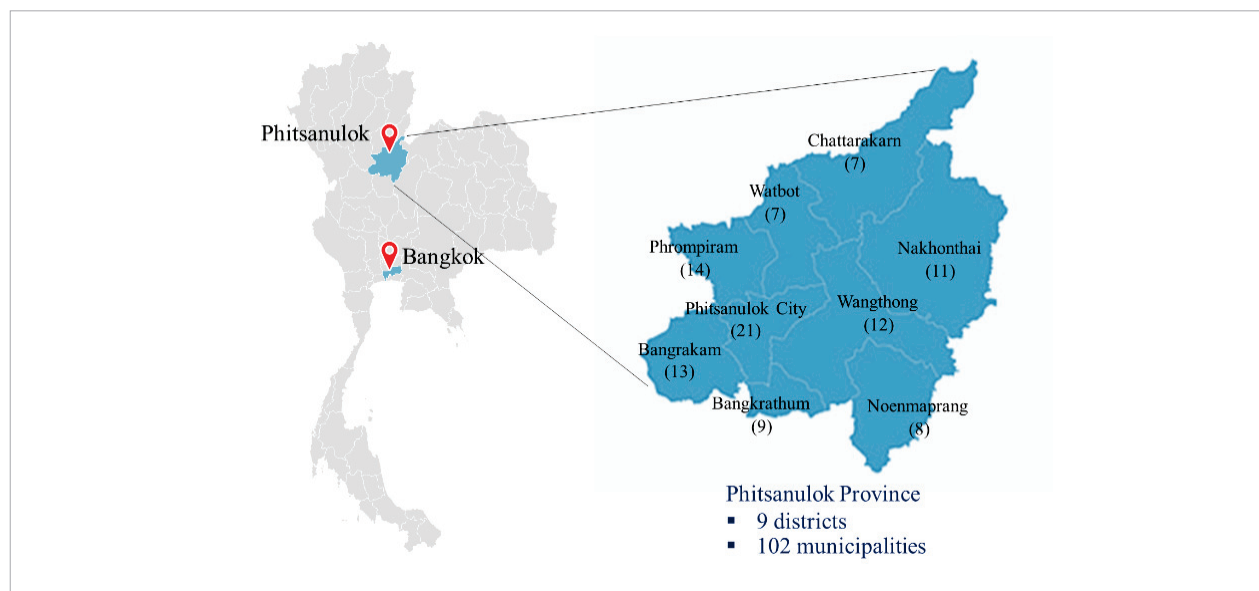
This study selected Phitsanulok Province, Thailand, as a case study because it is a major province in the lower northern region and includes a full range of local administrative organization (LAO) types, namely city municipality, town municipality, subdistrict municipality, and subdistrict administrative organization (SAO). In Thailand, LAOs except Bangkok are established based on population size, urbanization level, and administrative capacity; therefore, not all provinces contain every type of municipality. Phitsanulok Province provides a representative case as it encompasses all municipality types within a single provincial boundary, allowing for comprehensive comparison across administrative structures.

The province covers an area of 10,815.8 km², representing 6.4% of the northern region and 2.1% of the country's total area (OPCAP, 2025). It is located

approximately 377 km north of Bangkok by road. The population is about 840,000 with 49% male and 51% female (PPLO, 2024). Administratively, Phitsanulok Province consists of nine districts: Chattrakarn, Nakhonhai, Noenmaprang, Bangkrathum, Bangrakam,

Phrompiram, Phitsanulok City, Wangthong, and Watbot. In total, there are 102 municipalities distributed across these districts, comprising one city municipality, one town municipality, 24 subdistrict municipalities, and 76 SAOs, as shown in Fig. 1.

Fig. 1. Map of Phitsanulok Province showing the number and distribution of municipalities



Data collection and analysis

The data collection process was conducted over a six-month period during 2024–2025 (from October 2024 to March 2025) and was structured into two primary steps: (i) MSW management data and (ii) MSW composition data. MSW management data included information on waste quantity (tonnes/year) by type (general waste, organic waste, recyclable waste, and hazardous waste), MSW vehicle type, end-of-life management, landfill or incinerator location, population, fuel type, and number of collection rounds per day. These data were obtained through questionnaire surveys distributed to all municipalities in Phitsanulok Province. Prior to data collection, the questionnaire was reviewed and validated during a seminar session with municipal staff to ensure clarity, relevance, and consistency with local waste management practices. The responses were based on existing municipal records and databases. To enhance data reliability, completed questionnaires were cross-checked for completeness and internal consistency, and any unclear or inconsistent entries

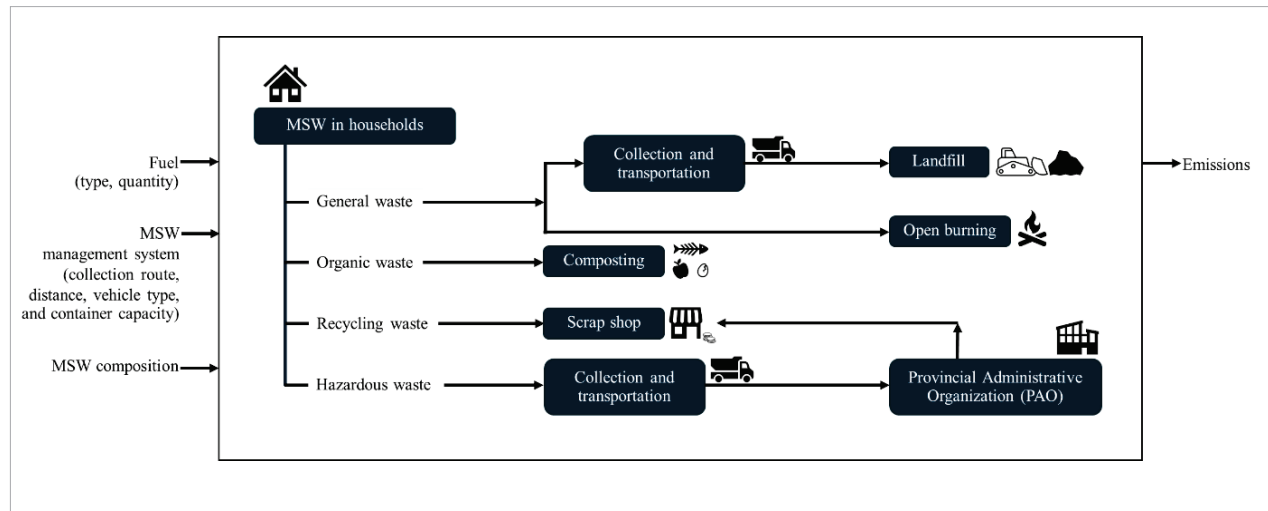
were verified through follow-up communication with the respective municipalities. Subsequently, the data was compiled and analyzed in Microsoft Excel.

MSW composition data were obtained through direct sampling of general household waste of at least 10 kg, which was characterized using the quartering method (i.e., mixing, quartering, selecting two opposite parts, re-mixing, and weighing with a portable digital scale) (Rojas-Valencia and Nájera-Aguilar, 2012). The weight of each waste category was compared to the total weight of the pooled sample to determine proportional composition. Sampling was conducted across three areas to obtain representative average values for MSW composition.

GHG emissions evaluation

The GHG emissions assessment followed a LCA framework as defined by ISO 14040 (ISO, 2006). The system boundary covered MSW management from household generation through transportation and end-of-life treatment (Fig. 2). The functional unit was defined as

Fig. 2. System boundary for the GHG emissions assessment



tonnes CO₂-eq per municipality per year. GHG emissions were estimated using Equation 1.

$$\text{GHG emission} = \text{Activity data} \times \text{Emission factor} \quad (1)$$

where *GHG emission* – kg CO₂-eq/municipality/year; *activity data* – quantitative parameters such as MSW quantity (tonnes/municipality/year); *emission factor* (EF) – the GHG emissions per unit of activity (e.g., kg CO₂-eq/kg), except for combustion, EF values were obtained from the Thailand Greenhouse Gas Management Organization (TGO) database (TGO, 2022).

This study considered four main types of MSW, including general waste, organic waste, recyclable waste, and hazardous waste. For general waste, not all municipalities operate a collection system. Where collection is available, waste is transported to a sanitary landfill. In municipalities without formal collection, residents typically dispose of waste through open burning. In Phitsanulok Province, some municipalities operate small-scale programs to collect and compost organic waste, reflecting the city's semi-urban context outside major capital cities. For recyclable waste, residents often separate valuable materials such as glass bottles, plastic bottles, and cardboard for sale to junk shops or scrap shops. For hazardous waste (e.g., light bulbs, batteries, spray cans, and medicine bottles), municipalities collect and transfer these materials to the Phitsanulok provincial administrative organization (PAO), which subsequently sells them to scrap shops

due to their residual economic value. The emission factors applied in this study are presented in *Table 1*. Most emission factors were obtained from the TGO database, as it provides nationally standardized emission factors developed for Thailand's GHG inventory. These factors are derived from a combination of country-specific data and internationally recognized methodologies, e.g., the Intergovernmental Panel on Climate Change (IPCC) guidelines, and are regularly updated to reflect local conditions. They are considered representative of typical waste management practices across Thailand, making them suitable for application in Phitsanulok Province as well. The use of this database ensures consistency with national GHG accounting frameworks and enhances the reliability and comparability of the results within the Thai context. End-of-life emissions from waste streams that generated economic benefit (e.g., recycling) were assumed to be zero.

For transportation, only general waste and hazardous waste transport were included in the GHG emissions assessment, as these are managed directly by local governments. For general waste transport, municipalities typically use 10-wheel trucks with a maximum load capacity of 16 tonnes, powered by diesel. For hazardous waste transport, small 4-wheel trucks with a maximum load capacity of 7 tonnes, powered by diesel, were used to transfer waste to the PAO. The EFs for transportation are presented in *Table 1*. Round-trip transportation (outbound and return) was assessed separately because the corresponding EFs differed.

Table 1. Emission factors in this study

Emission factor	Value	Unit	Reference
Sanitary landfill	0.7933	kg CO ₂ -eq/kg MSW	TGO (2022)
Organic compost	0.3326	kg CO ₂ -eq/kg organic waste	TGO (2022)
Selling to scrap shop	0.0000	kg CO ₂ -eq/kg MSW	TGO (2022)
General waste transport (with loading)	0.0533	kg CO ₂ -eq/tkm	TGO (2022)
General waste transport (without loading)	0.5900	kg CO ₂ -eq/km	TGO (2022)
Hazardous waste transport (with loading)	0.2698	kg CO ₂ -eq/tkm	TGO (2022)
Hazardous waste transport (without loading)	0.3131	kg CO ₂ -eq/km	TGO (2022)
Open burning	1.0346	kg CO ₂ -eq/kg MSW	This study's calculation

For the open-burning case, emission factors were calculated based on MSW composition following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). Equations 2–5 were applied to estimate emissions of carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and total GHG emissions, respectively.

$$\text{CO}_2 \text{ emission} = \sum_j (WF_j \cdot dm_j \cdot CF_j \cdot FCF_j \cdot OF_j) \cdot \frac{44}{12} \quad (2)$$

where *CO₂ emission* – kg CO₂-eq/kg MSW, *WF_j* – the wet weight fraction of MSW component *j*, *dm_j* – the dry matter content in the component *j* of MSW, *CF_j* – the carbon fraction of component *j*, *FCF_j* – the fossil carbon fraction of component *j*, *OF_j* – the oxidation factor, *44/12* – a conversion factor from C to CO₂, *j* – the component of the MSW.

The parameters *dm*, *CF*, *FCF*, and *OF* were obtained from the IPCC default value (IPCC, 2006). To account for biogenic carbon emissions, this study assumed *FCF* = 100% for all waste components, except for recyclable waste, which was set at *FCF* = 0. This assumption represented a conservative, worst-case scenario, as it assumed that all carbon in non-recyclable waste is fully oxidized to CO₂. In practice, biogenic waste components, e.g., food and garden waste, textile waste, paper waste, and rubber waste, are typically treated differently in GHG accounting, resulting in lower effective fossil carbon contributions (Sununta and Sampattagul, 2019; Kwon et al., 2023). Therefore, the approach used in this study may lead to higher emission estimates compared to studies that apply more detailed biogenic carbon accounting methods.

$$\text{CH}_4 \text{ emission} = \sum_j (IW_j \cdot EF \cdot GWP_j) \quad (3)$$

where *CH₄ emission* – kg CO₂-eq/kg MSW, *IW_j* – the weight fraction of MSW component *j*, *EF* – the emission factor for open burning (6500 g CH₄/tonnes MSW) (IPCC, 2006).

Moreover, the global warming potential (GWP) of methane was set at 27 kg CO₂-eq/kg CH₄ for non-fossil sources, and 29.8 kg CO₂-eq/kg CH₄ for fossil-based methane (e.g., plastics) (IPCC, 2024).

$$\text{N}_2\text{O emission} = \sum_j (IW_j \cdot dm_j \cdot EF \cdot GWP) \quad (4)$$

where *N₂O emission* – kg CO₂-eq/kg MSW.

EF for N₂O emission was 150 g N₂O/t dry waste, and *GWP* was set at 273 kg CO₂-eq/kg N₂O (IPCC, 2006; IPCC, 2024).

$$\text{Total emission} = \text{CO}_2 \text{ emission} + \text{CH}_4 \text{ emission} + \text{N}_2\text{O emission} \quad (5)$$

where *Total emission* – kg CO₂-eq/kg MSW, which was used as *EF* for open burning.

To estimate GHG emissions following Equation 1, the total MSW quantity (tonnes/municipality/year) was multiplied by the result of Equation 5.

Results and Discussion

MSW management data of municipalities

MSW management data were collected from 50 municipalities in Phitsanulok Province through questionnaire

surveys. *Table 2* presents the number of surveyed municipalities distributed by district and municipality type. Data were fully collected for city and town municipalities (100% each), while 50% of subdistrict municipalities and 47% of SAOs were surveyed. The collected data included annual waste generation by type (general, organic, recyclable, and hazardous), collection practices, transportation systems, and end-of-life management methods. *Table 3* provides examples of MSW management characteristics by municipality type. Among all municipalities, Phitsanulok City, a city municipality, exhibited the highest MSW generation, reflecting its high population density.

MSW compositions

Analysis of average MSW compositions from three areas revealed that organic waste accounted for 37% of the total waste. Plastics were the second most abundant component at 35%, followed by infectious waste (e.g., tissues, diapers, sanitary napkins) at 16%. Recyclable waste, including tin cans and glass bottles, comprised 3%, while cardboard boxes (milk cartons, medicine boxes) accounted for 3%. Other paper types accounted for 4%, and miscellaneous items accounted for the remaining 2% of the MSW stream. These results highlight the dominance of organic and plastic waste in the municipal waste stream. Notably, the proportion of organic waste (37%) was lower than the national average of 48%, whereas the fraction of plastic waste exceeded the national average of 29% (PCD, 2024). This discrepancy can be attributed to the semi-urban context of Phitsanulok Province, where a substantial portion of organic waste is repurposed as animal feed or compost, resulting in a relative increase in the plastic fraction. Similar patterns have been observed in Nakhon

Table 2. Number of collected municipalities

District	City	Town	Subdistrict	SAO	Total
Bangkrathum			2	5	7
Bangrakam			3	5	8
Chattarakarn				3	3
Nakhonthai			1	6	7
Noenmaprang			3	2	5
Phitsanulok City	1	1	2	6	10
Phrompiram				2	2
Wangthong				2	2
Watbot			1	5	6
Total	1	1	12	36	50
% Collection rate	100	100	50	47	49

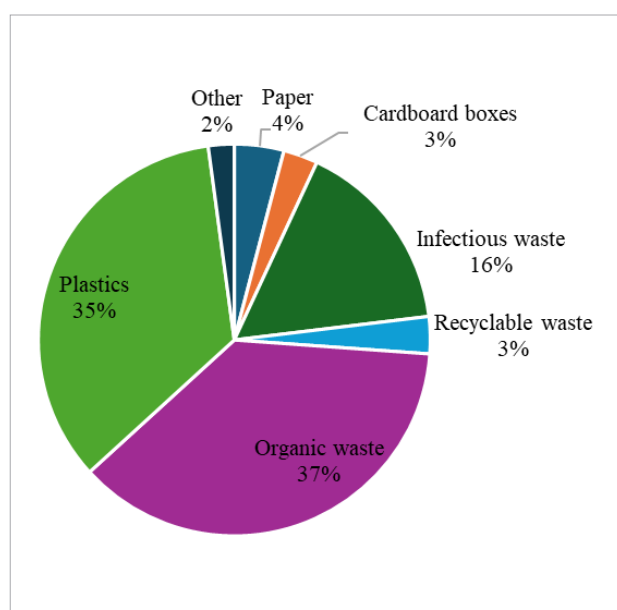
Si Thammarat Municipality, where organic and plastic waste together accounted for a dominant proportion of total waste (73–95%) (Jawjit et al., 2025). Organic waste is often transformed into valuable products such as animal feed, compost, or liquid fertilizer, contributing to reduced landfill disposal and supporting circular economy practices at the local level (Jawjit et al., 2025; Sununta et al., 2018; Ma et al., 2024). When organic waste is separated at the household level, the amount of mixed MSW requiring landfill disposal or open burning is reduced, thereby altering overall waste generation patterns and increasing the relative proportion of other waste fractions. These findings highlight that active community participation plays a critical role in shifting waste flows from disposal-oriented pathways toward resource recovery. However, the effectiveness of such practices depends on the availability of formal waste

Table 3. Examples of surveyed municipalities in Phitsanulok Province and their characteristics

Municipality	Municipality type	Population (capita)	General waste (tonnes/year)	Organic waste (tonnes/year)	Recyclable waste (tonnes/year)	Hazardous waste (tonnes/year)	General waste collection system	Hazardous waste collection system	End-of-life general waste
Phitsanulok City	City municipality	63,882	33,408.00	1928.00	1460.00	2.37	Yes	Yes	Sanitary landfill
Aranyik	Town municipality	29,292	4760.00	1240.00	-	0.16	Yes	Yes	Sanitary landfill
Sanam Khli	Subdistrict municipality	1676	107.64	525.03	271.50	0.13	No	Yes	Open burning
Mae Raka	SAO	7016	73.11	1559.73	731.13	24.37	No	Yes	Open burning

management systems. In this study, only 17 out of 50 municipalities had established MSW collection services, while the remaining municipalities relied on self-management by residents, often leading to open burning as a common disposal method (Pansuk et al., 2018). This suggests that limited infrastructure, together with varying levels of community engagement, significantly influences both waste generation patterns and associated GHG emissions. The waste composition data were subsequently used to calculate emission factors for open burning in the LCA-based GHG analysis. Fig. 3 shows the MSW compositions of Phitsanulok Province.

Fig. 3. Average MSW composition in this study



GHG emissions

The average GHG emissions per municipality were calculated from the total emissions of all surveyed municipalities. The results showed that each municipality emitted approximately 1999.19 tonnes CO₂-eq on average, as shown in Table 4. GHG emissions from MSW management are strongly influenced by factors such as population, residents' behavior, waste generation rates, waste composition, transportation, and disposal practices (Outapa and Na Roi-et, 2018; Rotthong et al., 2023; Jawjit et al., 2025; Sununta and Sampattagul, 2019; Sutthasil et al., 2023). Variations in these factors lead to significant differences in emission levels across regions and administrative hierarchy.

Table 4. GHG emissions based on activity

Activity	Total GHG emissions from 50 municipalities (tonnes CO ₂ -eq/year)	Average GHG emissions (tonnes CO ₂ -eq/municipality/year)
General waste transport to sanitary landfill	128.68	2.57
Hazardous waste transport to PAO	16.79	0.34
Sanitary landfill	56,581.37	1131.63
Open burning	35,863.17	717.26
Organic waste compost	7369.51	147.39
Total	99,959.53	1999.19

Among the different waste management activities examined in this study, emissions from sanitary landfills were the largest contributor, totaling 56,581.37 tonnes CO₂-eq (1131.63 tonnes CO₂-eq/municipality), followed by open burning of waste at 35,863.17 tonnes CO₂-eq (717.26 tonnes CO₂-eq/municipality). General waste transport to sanitary landfills contributed 128.68 tonnes CO₂-eq total (2.57 tonnes CO₂-eq/municipality), hazardous waste transport to PAO accounted for 16.79 tonnes CO₂-eq total (0.34 tonnes CO₂-eq/municipality), and organic waste composting had the lowest contribution at 7369.51 tonnes CO₂-eq total (147.39 tonnes CO₂-eq/municipality). These results indicate that landfill operations and open burning are the dominant sources of municipal GHG emissions, together accounting for 92.48% of total emissions. The high emissions from landfills reflect both the large volumes of waste disposed of and the decomposition of organic matter under anaerobic conditions, producing methane and carbon dioxide. Supporting this, MSW decomposition in landfill environments can generate GHG emissions averaging 96.06 mg CO₂-eq/L of leachate per day, with emissions tending to increase after approximately three weeks (Lertyingcharoenchai et al., 2019). This pattern reflects the sequential biodegradation processes occurring within landfills. Initially, aerobic decomposition dominates due to the presence of residual oxygen during waste placement. As oxygen is depleted, the system transitions to anaerobic conditions, where organic matter is degraded through microbial processes, ultimately leading to methane

production during the methanogenesis phase. As a result, GHG emissions continue to increase over time and may persist for 20-30 years until landfill stabilization or final cover is achieved (Lou and Nair, 2009). Open burning, while smaller than landfills, remains a significant contributor because it combusts organic and plastic waste, generating substantial CO₂ and other pollutants. This finding is consistent with previous studies in Thailand, which have identified landfill disposal as the primary contributor to emissions due to anaerobic decomposition of organic waste (Outapa and Na Roi-et, 2018; Sununta and Sampattagul, 2019). Specifically, Outapa and Na Roi-et (2018) reported that disposal processes accounted for 98.86% of total emissions, while Sununta and Sampattagul (2019) reported a similarly high contribution of 99.13%. Similar trends have also been reported in other developing countries, where limited waste segregation and reliance on landfill disposal and open burning result in high emissions from these sources (Verma and Borongan, 2022; Babel and Vilaysouk, 2016; Kristanto and Koven, 2019). For instance, Verma and Borongan (2022) reported that approximately 99% of total GHG emissions originated from disposal sites. In comparison, the contribution of 92.48% observed in this study is slightly lower than the values reported in previous studies in Thailand and other developing countries (typically around 98-99%), but remains within the same dominant range, indicating a broadly consistent emission pattern while reflecting differences in waste management practices.

In contrast, emissions from waste transport and organic waste composting were relatively minor. This aligns with findings from other regional studies, which report that transportation contributes only a small fraction of total emissions compared to treatment and disposal processes (Outapa and Na Roi-et, 2018; Jawjit et al., 2025; Sunaryo et al., 2023). This suggests that strategies to reduce emissions should prioritize landfill management improvements, such as methane capture, and the reduction or control of open burning practices. Promoting composting and waste segregation could further mitigate GHG emissions by diverting organic waste from landfills and reducing the amount of waste subject to uncontrolled combustion or using carbon capture technologies, consistent with the recommendations of other studies (Oo et al., 2024; Sunaryo et al., 2023; Ngumah et al., 2013). Moreover, door-to-door MSW collection could increase collection

rates and help avoid waste mismanagement (Kokkinos et al., 2025). Overall, these findings underscore the importance of targeting high-impact activities for sustainable waste management and municipal-level climate action planning.

Table 5 presents average GHG emissions per municipality from MSW management across different types of municipalities. The average GHG emissions were highest in city municipality, at 26,530.62 tonnes CO₂-eq/municipality/year, followed by town municipality (4205.72 tonnes CO₂-eq/municipality/year), 1836.52 tonnes CO₂-eq/municipality/year for subdistrict municipalities, and 1167.55 tonnes CO₂-eq/municipality/year for SAOs. This trend is consistent with Saiphet and Kunta (2023), who reported that city municipalities tend to generate higher GHG emissions compared to other types of municipalities. For city municipalities, Outapa and Na Roi-et (2018) estimated total emissions of approximately 21,000 tonnes CO₂-eq/year in Lampang Municipality, while Jawjit et al. (2025) reported a higher total of 63,086 tonnes CO₂-eq/year in Nakhon Si Thammarat Municipality. In this study, the city municipality exhibited emissions of 26,531 tonnes CO₂-eq/year, which are higher than those reported for Lampang Municipality but lower than those for Nakhon Si Thammarat Municipality. These differences can be largely attributed to variations in population size. Lampang Municipality has approximately 46,965 registered residents, compared to 63,882 in Phitsanulok City Municipality and 93,617 in Nakhon Si Thammarat Municipality (BORA, 2026). In contrast, subdistrict municipalities generally exhibit lower emissions than city and town municipalities, consistent with the findings of this study. For instance, Sununta et al. (2018) reported emissions of 1124 tonnes CO₂-eq/year for Dan Sai Municipality, whereas Lertyingcharoenchai et al. (2019) estimated emissions of 676 tonnes CO₂-eq/year for Takhob Municipality, a subdistrict municipality in Nakhon Ratchasima Province. These lower emission levels reflect the smaller population size and reduced waste generation rates typically associated with such administrative units (Sununta et al., 2018; Lertyingcharoenchai et al., 2019).

When normalized by population, the average per capita emissions were highest in city municipality (0.42 tonnes CO₂-eq/capita/year) and lower in town municipality (0.14 tonnes CO₂-eq/capita/year), subdistrict municipalities (0.20 tonnes CO₂-eq/capita/year), and

Table 5. GHG emissions based on municipality type

Municipality	Average population (capita)	Average GHG emissions (tonnes CO ₂ -eq/municipality/year)	Average GHG emissions (tonnes CO ₂ -eq/capita/year)
City municipality	63,882	26,530.62	0.42
Town municipality	29,292	4205.72	0.14
Subdistrict municipality	9103	1836.52	0.20
SAO	6372	1167.55	0.18

SAOs (0.18 tonnes CO₂-eq/capita/year). The higher per capita emissions in the city municipality can be attributed to larger waste generation rates per person and greater reliance on landfill disposal and open burning. Comparable trends have been reported in other Thai city municipalities. For example, Lampang Municipality and Nakhon Si Thammarat Municipality reported per capita emissions in the range of 0.45–0.67 tonnes CO₂-eq/capita/year, which are similar to the values observed in this study (Outapa and Na Roi-et, 2018; Jawjit et al., 2025). In contrast, town municipalities exhibited lower per capita emissions, reflecting smaller populations and lower waste generation rates, thereby highlighting the influence of population size on emission intensity. Subdistrict municipalities and SAOs showed lower total and per capita emissions, which can be attributed to smaller populations and a greater tendency to divert organic waste through composting or use as animal feed, reducing landfill-related methane emissions. Although the average per capita emissions for subdistrict municipalities in this study were lower than those reported for Dan Sai Municipality (0.30 tonnes CO₂-eq/capita/year) and higher than those reported for Takhob Municipality (0.13 tonnes CO₂-eq/capita/year), the observed range (0.01–0.42 tonnes CO₂-eq/capita/year) indicates considerable variability, likely influenced by differences in local waste management practices and residents' behavior (Sununta et al., 2018; Lertyingcharoenchai et al., 2019; Saiphet and Kunta, 2023). Similar variability has been observed in other Southeast Asian countries. For instance, per capita emissions from MSW management have been reported at approximately 0.28 tonnes CO₂-eq/capita/year in Ho Chi Minh City, Vietnam; 0.39 tonnes CO₂-eq/capita/year in Surabaya City, Indonesia;

and 0.15 tonnes CO₂-eq/capita/year in Vientiane, Lao PDR (Babel and Vilaysouk, 2016; Verma and Borongan, 2022; Liem et al., 2024). These findings suggest that highly urbanized cities with larger populations tend to generate higher GHG emissions, consistent with the city municipality results in this study, whereas smaller or less densely populated areas exhibit lower emission levels, similar to town municipalities, subdistrict municipalities, and SAOs.

So, it could indicate that municipality type and population density are key factors influencing GHG emissions from waste management (Saiphet and Kunta, 2023). Mitigation strategies should therefore be tailored according to municipality type: for city municipalities, interventions such as improved landfill management, waste-to-energy technologies, and promotion of waste segregation could substantially reduce per capita emissions, while for smaller municipalities, expanding composting programs and minimizing open burning could be most effective.

For the prediction across the entire Phitsanulok Province, total GHG emissions from 102 municipalities were estimated at 163,546.78 tonnes CO₂-eq/year as presented in *Table 6*. The largest contribution came from SAOs, which, with 76 municipalities, accounted for 88,734.05 tonnes CO₂-eq/year. Although individual city municipalities exhibited the highest emissions per municipality, the cumulative effect of the numerous SAOs resulted in their dominant share of total regional emissions. These predicted emissions provide a valuable basis for developing region-specific waste management strategies and municipal-level climate action plans, highlighting the need to tailor mitigation measures according to municipality type and population distribution.

Table 6. GHG emissions prediction in Phitsanulok Province

Municipality	Number of municipalities	Average emissions (tonnes CO ₂ -eq/municipality/year)	Total emissions (tonnes CO ₂ -eq/year)
City municipality	1	26,530.62	26,530.62
Town municipality	1	4205.72	4205.72
Subdistrict municipality	24	1836.52	44,076.40
SAO	76	1167.55	88,734.05
Total	102		163,546.78

Limitations

This study provides a comprehensive assessment of GHG emissions from MSW management in Phitsanulok Province; however, several limitations should be acknowledged. First, the dataset covers 50 out of 102 municipalities, which may limit the representativeness of the findings. Future studies should aim to include all municipalities to improve coverage and robustness. Second, temporal variations in waste generation and composition, such as seasonal fluctuations, were not explicitly analyzed, which may affect the accuracy of annual emission estimates. Long-term and multi-season data collection would help address this limitation. Third, the assumption of a worst-case scenario for fossil carbon content (FCF=100% for non-recyclable waste) may lead to overestimation of GHG emissions compared to approaches that apply more detailed biogenic carbon accounting. Finally, the analysis of municipality types is constrained by the limited number of city and town municipalities in Phitsanulok Province (one each), which may reduce the generalizability of comparisons across administrative categories. Future research should expand the analysis to include municipalities from other provinces for broader applicability.

Recommendations for MSW management

Despite the limitations outlined above, the findings of this study provide a basis for several policy and management recommendations to reduce GHG emissions from MSW management in Phitsanulok Province.

(i) Promote organic waste segregation, and composting programs, particularly in city municipalities and high-emission SAOs. Organic waste constitutes the largest fraction of MSW and significantly contributes to GHG emissions. Increasing source separation of organic waste can substantially reduce emissions from landfill disposal and open burning (Liem et al., 2024; Phonphoton and Tongsuntud, 2026; Ma et al., 2024; Jawjit et al., 2025). In this study, a scenario assuming 100% source separation and composting of organic waste could reduce emissions by approximately 611.20 tonnes CO₂-eq/municipality/year, representing a reduction of 30.57%, despite emissions generated during the composting process. Moreover, previous studies suggest that even a 30% composting rate can achieve considerable GHG emission reductions (Liem et al., 2024). However, seasonal variations in the quantity and composition of organic waste may affect the feasibility

and efficiency of composting systems (Phonphoton and Tongsuntud, 2026).

(ii) Promote waste-to-energy technologies, particularly through the utilization of plastic waste for refuse-derived fuel (RDF) to replace fossil fuels such as coal in power generation. Plastic waste was the second-largest fraction of MSW in this study and had high energy recovery potential. A scenario assuming complete separation of plastic waste could reduce GHG emissions by up to 574.17 tonnes CO₂-eq/municipality/year (28.72%). Previous studies report that emissions associated with plastic waste management can be reduced by approximately 85–98% when effectively diverted from landfill (Piboon et al., 2022; Panida et al., 2023). Additionally, integrated waste-to-energy systems have been shown to reduce overall waste-related GHG emissions by approximately 50–60% (Sari et al., 2025). The lower reduction observed in this study reflects the continued disposal of residual waste in landfills.

(iii) Improve landfill management through methane capture systems to further reduce GHG emissions, especially in city municipalities or urban areas where large volumes of MSW are generated and waste collection and transportation systems are already well established. Landfill gas collection systems have been shown to reduce GHG emissions by approximately 45–75% of total emissions from MSW landfills, depending on system efficiency and operational conditions (Oonk, 2012; Boongla et al., 2025).

(iv) Strengthen regulations and improve MSW collection systems to minimize uncontrolled open burning, particularly in semi-urban and rural areas. In areas lacking formal waste collection and transportation systems, residents often resort to open burning as a convenient disposal method. Expanding and improving MSW collection infrastructure would significantly reduce such practices and associated emissions. In addition to environmental impacts, open burning poses serious health risks, including respiratory irritation, carcinogenic and mutagenic effects, neurotoxicity, and damage to the eyes and mucous membranes due to exposure to toxic emissions (Pathak et al., 2023).

(v) Enhance public awareness and capacity building by educating residents and municipal staff on sustainable waste management practices. Community-driven initiatives have been shown to achieve participation rates of up to 95%, highlighting their potential effectiveness

in improving waste segregation and reduction (Xiao et al., 2023). However, such initiatives should be supported by adequate MSW infrastructure and management systems across all municipality types to ensure long-term effectiveness.

These suggestions highlight that targeted, municipality-specific strategies can achieve substantial GHG emission reductions and support the transition toward low-carbon waste management systems.

Conclusions

This study assessed GHG emissions from MSW management across 50 municipalities in Phitsanulok Province, Thailand, using a LCA approach. The results showed that the average GHG emission was 1999.19 tonnes CO₂-eq/municipality/year, with total emissions reaching 99,959.53 tonnes CO₂-eq/year. Emissions were dominated by landfill operations and open burning, while the city municipality exhibited the highest emissions per municipality. In contrast, SAOs contributed the largest share of total emissions due to their high number. At the provincial scale, total emissions from all 102 municipalities were estimated at 163,546.78 tonnes CO₂-eq/year, with SAOs as the largest contributors. Waste composition, population size, and municipality type were identified as key factors influencing emission levels.

This study is subject to limitations, including partial survey coverage (50 out of 102 municipalities), lack of seasonal variation analysis, the use of a conservative worst-case assumption for fossil carbon content (FCF = 100% for non-recyclable waste), and limited representation of city and town municipalities, which may

affect the accuracy and generalizability of the results. Nevertheless, this study provides one of the first comprehensive provincial-scale assessments covering all municipality types.

Based on these findings, targeted mitigation strategies are recommended. Municipalities with established MSW collection systems, particularly city and town municipalities, should prioritize waste separation to promote organic waste composting, plastic waste utilization for energy recovery, and landfill improvement through methane capture. In contrast, municipalities lacking collection and transportation systems, especially SAOs, should focus on expanding MSW infrastructure to reduce open burning practices. These efforts should be complemented by public awareness and capacity-building initiatives to ensure long-term effectiveness and sustainability. Furthermore, similar assessments should be conducted in other provinces to enable regional comparisons, improve national GHG inventories, and support the development of scalable waste management and climate mitigation strategies.

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