Environment and Natural Resources Journal

Volume 24
Issue 6
2026

Scenario-Based Assessment of Greenhouse Gas Mitigation in the Municipal Solid Waste: Cambodia Case Study and Regional Comparison in Asia

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ARTICLE INFO

Received: 5 Jan 2026
Received in revised: 19 Jun 2026
Accepted: 24 Jun 2026
Published online: 3 Sep 2026
DOI: 10.32526/ennrj/24/20260009

Keywords:
Solid waste management/ GHG mitigation/ Policy/ Asia/ Cambodia

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ABSTRACT

This study estimates future waste generation and evaluates greenhouse gas (GHG) mitigation potential under alternative waste management strategies in Cambodia. Key mitigation measures include waste reduction, improved collection efficiency, recycling, and methane recovery. Recycling is identified as the most effective option, contributing approximately 60% and 77% of total GHG reductions in 2030 and 2050, respectively, while methane recovery provides an additional 28% in 2030 and 22% in 2050. Under the Business-as-Usual (BaU) scenario, waste-sector GHG emissions are projected to increase from 1.6 $MtCO_2eq$ in 2010 to 5.7 $MtCO_2eq$ in 2030 and 15.2 $MtCO_2eq$ in 2050. A regional comparison indicates that Cambodia's waste-related GHG emissions are high relative to its income level and are comparable to those of more developed countries such as Japan, while exceeding those of Singapore, primarily due to limited waste treatment capacity and a high organic fraction in waste. Implementation of countermeasure strategies could reduce emissions by 13% in 2030 and 39% in 2050 compared to the BaU scenario, demonstrating substantial mitigation potential in Cambodia's waste sector. The study employs the Extended Snapshot (ExSS)/Waste model (a bottom-up engineering approach) and provides evidence-based insights to support climate-oriented waste management policy in Cambodia and comparable developing countries in the region.

HIGHLIGHTS

- Cambodia's waste-sector GHG emissions are projected to rise from 1.6 to 15.2 $MtCO_2eq$ by 2050 under BaU.
- Industrial waste dominates future emissions, exceeding 70% of total waste-sector GHG by 2050.
- Countermeasure strategies can reduce emissions by 13% in 2030 and 39% in 2050 vs. BaU.
- Recycling accounts for about 77% and methane recovery for about 22% of total reductions by 2050.
- The ExSS/Waste model provides a transferable framework for GHG mitigation in developing Asia.

1. INTRODUCTION

Inappropriate waste management practices lead to emissions of methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O), which contribute significantly to climate change. Over a 100-year time horizon, methane has a global warming potential approximately 27.2 without climate-carbon feedbacks and 29.8 with feedbacks relative to CO_2 (IPCC, 2021). Globally, methane emissions from waste disposal sites account for approximately 10-12% of total anthropogenic methane emissions, representing nearly half of emissions attributed to the waste sector (US EPA, 2006; IPCC, 2007).

Although the waste sector contributes only about 3-5% of total global GHG emissions, it is increasingly recognized as a key mitigation sector due to its high reduction potential through alternative treatment technologies and improved management systems (UNFCCC, 2005; Ragossnig and Hilger, 2008; IPCC, 2019). Measures such as waste minimization, recycling, composting, and methane recovery can substantially reduce upstream and downstream GHG emissions.

Citation: Take K, Nguyen T-H. Scenario-based assessment of greenhouse gas mitigation in the municipal solid waste: Cambodia case study and regional comparison in Asia. Environ. Nat. Resour. J. 2026;24(6):701-712. (https://doi.org/10.32526/ennrj/24/20260009)

In Cambodia, municipal waste generation has increased rapidly in recent years, reflecting the country's rapid urbanization, economic growth, and expansion of the tourism sector. Municipal solid waste generation in Cambodia exceeded 3 Mt/year by the late 2010s, driven by rapid urbanization, economic growth, and tourism development (Ministry of Environment, 2025; World Bank, 2021). Per capita municipal solid waste generation in Cambodia has risen to around 0.6-0.7 kg/person/day in recent years, with higher levels in urban areas (World Bank, 2018; Ministry of Environment, 2025). Without effective intervention, inadequate waste management may lead to resource degradation, land scarcity, public health risks, and increased climate impacts.

Various models have been developed to estimate GHG emissions and mitigation potential in the waste sector. Inventory-based models, particularly those following the IPCC Waste methodology, are widely applied for national GHG reporting and mitigation assessment under the UNFCCC framework (IPCC, 2019; IPCC, 2022). Life cycle assessment (LCA)-based models, such as those reviewed in recent global assessments, are commonly used to compare technology-specific emission impacts of waste treatment options, including recycling, composting, and incineration (UNEP, 2024). In contrast, bottom-up scenario-based models, such as the Extended Snapshot (ExSS)/Waste model, are designed for long-term mitigation and policy analysis; recent applications in Vietnam and Malaysia indicate that waste-sector emissions could exceed 60 $MtCO_2eq$ by 2030 under Business-as-Usual conditions, while recycling and methane recovery could reduce emissions by more than 30% (Nguyen and Matsuoka, 2017; Siong et al., 2013).

This study addresses three specific objectives: (1) to project future solid waste and wastewater generation in Cambodia from 2010 to 2050; (2) to quantify GHG emissions under a Business-as-Usual (BaU) scenario; and (3) to evaluate mitigation potential under a Countermeasure (CM) scenario, with regional comparison across selected Asian countries. By assessing these mitigation scenarios, this paper provides evidence-based insights to support policy development and strategic planning for sustainable waste management in Cambodia. To the best of the authors' knowledge, this study represents one of the early national-scale assessments linking municipal waste management strategies and climate change mitigation in the Cambodian context.

2. METHODOLOGY

2.1 General model description

There are some models available to help determine the best options for reducing GHG emissions from waste (IPCC, 2006; US EPA, 2012). Among the models used to identify optimal strategies for reducing GHG emissions, the Extended Snapshot (ExSS)/Waste model, a bottom-up engineering model, is employed for estimation purposes. The model quantifies GHG emissions from three main sources: (1) fossil CO_2 released during incineration of fossil-derived waste; (2) CH_4 generated from the decomposition of organic carbon in disposed solid waste and from wastewater treatment; and (3) N_2O from wastewater treatment.

For solid waste disposal, the model applies the First-Order Decay (FOD) method (IPCC Tier 1) to capture the delayed release of methane following waste burial, with methane correction factor (MCF) and degradable organic carbon (DOC) serving as key parameters. For wastewater, GHG emissions are estimated on a per-person basis using BOD/COD activity data. Because this methodology is applied at the individual level, emissions from commercial wastewater are incorporated into the domestic wastewater category. It should be noted that the model does not account for energy consumption or GHG emissions associated with energy use in waste management operations, nor does it include vehicle operation emissions.

The model encompasses the entire national waste system; however, the scenario analysis and modelling assessment focus specifically on the municipal waste system. Waste generation is categorized into two streams, solid waste and wastewater originating from the residential, commercial, industrial, and construction sectors. Population data and industrial output are provided to the ExSS/Waste model as exogenous inputs. The study covers the time horizon from 2010 to 2050. A detailed description of the model methodology is provided in Nguyen and Matsuoka (2017).

2.2 Scenarios description

The BaU scenario assumes the continuation of current waste generation trends and management practices without major additional interventions. Waste generation is projected based on population growth and economic development pathways consistent with Cambodia's transition toward upper-middle-income status by 2030 and high-income status

by 2050, as outlined in national development and climate policy frameworks (Royal Government of Cambodia, 2013; Ministry of Environment, 2025).

The CM scenario assumes accelerated implementation of waste management measures beyond existing plans, including higher recycling rates, expanded incineration, and enhanced methane recovery from disposal sites and wastewater treatment systems. Based on consultations with domestic experts and alignment with recent national climate commitments, the CM scenario assumes recycling of 40%, incineration of 6%, and methane recovery of 15% relative to the BaU scenario (IPCC, 2019; Ministry of Environment, 2025; IPCC, 2022). Socioeconomic assumptions are held constant across both scenarios to isolate the effects of waste management strategies.

The assumed future socio economic conditions of Cambodia are the same in both cenarios as follow:

Cambodia has maintained robust economic growth over the past decade, and the Government of the Kingdom of Cambodia has reaffirmed its long-term development objectives to attain upper-middle-income status by 2030 and high-income status by 2050, as outlined in national strategic frameworks (Royal Government of Cambodia, 2018). Achieving these targets requires sustained economic growth supported by structural transformation and macroeconomic stability. Population assumptions in this study are based on the United Nations World Population Prospects. Cambodia's population is projected to reach approximately 18.5 million by 2030 and around 22.0 million by 2050 under the medium-variant scenario, which is consistent with national development projections (United Nations, 2022).

2.3 Waste generation projection

2.3.1 Solid waste generation

Waste generation per capita in the residential sector for 2030 and 2050 is assumed to correspond to current upper-income and current high-income levels, respectively ("What a Waste"; Hoornweg and Bhada-Tata, 2012). Intermediate years between 2000 and 2050 are linearly interpolated. Solid waste in commercial, industrial and construction sectors are assumed to maintain the same generation factor as the base year. Since data is limited for Cambodia, and Vietnam is ahead of Cambodia in urbanization and per capita income, generation factors for these sectors are taken from Vietnam (Nguyen and Matsuoka, 2017). The resulting solid waste generation projections are summarized in Table 1.

Table 1. Solid waste generation

Indicator	Base year	Target year		References
	2010	2030	2050	
Population (person)	**13,959,000**	**18,391,000**	**21,964,000**	Statistic yearbook of Cambodia (National Institute of Statistic, 2024); World Population Prospects 2022 (United Nations, 2022)
- Urban	2,741,000	5,434,000	9,835,000	
- Rural	11,218,000	12,957,000	12,129,000	
Output of industry (million USD)	**28,334**	**119,549**	**486,468**	Chan and Oum (2011); Mao (2015); World Bank (2022), Ministry of Economy and Finance (MEF). (2023)
- Commercial sector	6,472	25,845	100,322	
- Industrial sector	10,635	45,480	187,596	
• Agriculture, fishery and forestry	3,136	9,265	30,082	
• Mining	125	558	2,338	
• Manufacturing	7,374	35,657	155,176	
- Construction sector	592	2,743	10,955	
Generation factor				
- Residential sector (kg/person/day)	0.3	0.6	1.3	Sethy (2013); Nguyen and Matsuoka (2017); UNEP (2024), Ministry of Environment (2025)
- Commercial sector (ton/million USD·year)	69.0	69.0	69.0	
- Industrial sector (ton/million USD·year)	64.8	64.8	64.8	
- Construction sector (ton/million USD·year)	431.8	431.8	431.8	
Waste generation (ton/year)	**2,919,392**	**10,074,706**	**34,142,096**	
- Residential sector	1,528,511	4,161,883	10,341,749	Estimated by multiplying waste generation per capita and population in the year

Table 1. Solid waste generation (cont.)

Indicator	Base year	Target year		References
	2010	2030	2050	
- Commercial sector	446,424	1,782,835	6,920,399	Estimated by multiplying waste generation factor in commercial sector and output of commercial sector in monetary units
- Industrial sector	688,802	2,945,617	12,149,988	Estimated by multiplying waste generation factor in industrial sector and output of industrial sector in monetary units
- Construction sector	255,656	1,184,371	4,729,959	Estimated by multiplying waste generation factor in construction sector and output of construction sector in monetary units

2.3.2 Wastewater generation

The activity data is used to calculate emissions from domestic wastewater treatment including population and degradable organic components or biochemical oxygen demand (BOD), while those for industrial wastewater treatment include industrial production and chemical oxygen demand (COD).

For domestic wastewater, GHG emissions are calculated using population and the IPCC default BOD per capita value of 14.6 kg BOD/capita/year (IPCC, 2006, Table 6-5, p. 6.23). The total domestic BOD load (kg/year) is obtained by multiplying this per capita factor by annual population. This BOD load is then used to estimate the maximum methane production capacity (B0), which, combined with the treated fraction and the methane correction factor (MCF) for each treatment system type, yields annual CH_4 emissions following IPCC Tier 1 methodology. The BOD generation factor is held constant from 2000 to 2050, consistent with IPCC default assumptions.

For industrial wastewater, only the main industries that process large volumes of organic wastewater with the largest potential for wastewater emission are considered, the value of COD differs between different industries (Table 2). The eneration factor in every year is assumed to be the same as that in 2010. Industrial wastewater was estimated by multiplying the wastewater generation factor in the industrial sector and the output of the industrial sector in monetary units in every year.

$$\text{Generation factor of 2010} = \frac{\text{Total COD/year}}{\text{Output of industry in 2010}} = \frac{6564.43}{10635.00} = 0.878\left(\frac{\text{ton COD}}{\text{million USD/year}}\right)$$

Table 2. Industrial wastewater generation in 2010

	Industrial production	Wastewater generated	Total wastewater generated	COD	Total organic degradable material in wastewater
Unit	ton/year	m^3/t	m^3/year	kgCOD/m^3	kgCOD/year
Beer and malt	159,285[(1)]	10.00[(3)]	1,592,850	3.50[(3)]	5,574,975
Fish processing	35,000[(1)]	21.50[(3)]	752,500	1.20[(3)]	903,000
Starch production	961[(2)]	9.00[(4)]	8,645	10.00[(3)]	86,455
Total	195,246	12.06	2,353,995		6,564,430

[(1)] FAO (2015), [(2)] Royal Government of Cambodia (2014a,b), [(3)] Nguyen and Matsuoka (2017), [(4)] IPCC (2006)

2.4 Waste composition

The study does not clarify the composition of wastewater; however, the composition of solid waste is defined in different sectors as below:

2.4.1 Residential and commercial solid waste

The composition of residential and commercial solid waste has some common characteristics such as a high rate of organic origin fraction; a high content of soil, sand, and brick and stone fragments; and high moisture content, with low specific heat energy (Nguyen, 2014). Socio-economic conditions that enable an increase in standards of living of the economy will influence the composition of the waste generated. The major types of residential and

commercial solid waste are food waste, paper, textile, plastic, metal, rubber, glass and other. In this study, the composition of solid waste in the two sectors in 2010 was derived from solid waste composition in Phnom Penh in Cambodia (Yim et al., 2023), and in 2030 and 2050 were assumed to be those in current upper income and current high-income sectors as reported by Hoornweg and Bhada-Tata (2012). As can be seen from Table 3, the largest percentage is the organic fraction at 66.3% (2010), and 54% (2030). Due to urbanization, the country will generate a high percentage of paper (14% in 2030 and 31% in 2050).

Table 3. Composition of residential and commercial solid waste

Waste composition (%)	2010[(1)]	2030[(2)]	2050[(2)]
Paper	4.6%	14.0%	31.0%
Textile	0.8%	2.0%	5.0%
Organic	66.3%	54.0%	28.0%
Wood	0.6%	0.6%	0.6%
Garden	0.2%	0.2%	0.2%
Rubber	0.4%	0.4%	0.4%
Plastic	9.8%	11.0%	11.0%
Metal	2.0%	3.0%	6.0%
Glass	3.0%	5.0%	7.0%
Other	12.5%	9.8%	10.9%

[(1)] Yim et al. (2023), [(2)] Hoornweg and Bhada-Tata (2012)

2.4.2 Industrial solid waste

Composition of industrial solid waste is very complicated, depending on the raw materials, technological processes and final products of each production center and its related services. There are various industries in Cambodia but information is lacking, therefore only one type of waste composition, namely "Other", was assumed for the industrial sector in this study. This simplification introduces uncertainty into industrial solid waste emission estimates. However, since industrial solid waste is predominantly non-organic relative to residential waste, the impact on total national GHG estimates is expected to be limited. Future studies should collect Cambodia-specific industrial waste composition data to refine these estimates.

2.4.3 Construction solid waste

Since no Cambodia-specific construction waste composition data is available, this study adopted composition data from Vietnam (Nguyen and Matsuoka, 2017), with one expert-adjusted modification: the wood fraction was reduced from 5% (Vietnam) to 2%, reflecting differences in construction practices.We assumed that waste composition would not change during the period 1990 to 2050. The waste composition waste is separated into metal (0.83%), brick (1.16%), concrete (65.83%), wood (2.00%), soil and sand (26.93%), and other (3.25%).

2.5 Waste management strategy

Cambodia's waste management framework is founded on early regulatory instruments, including the Sub-Decree on Solid Waste Management (Royal Government of Cambodia, 1999a) and the Sub-Decree on Water Pollution Control (Royal Government of Cambodia, 1999b), which continue to provide the legal basis for waste governance. More recently, waste management has been increasingly integrated into national climate policy through the Cambodia Updated Nationally Determined Contribution (NDC 3.0), submitted by the Ministry of Environment in 2025. NDC 3.0 commits Cambodia to an enhanced economy-wide greenhouse gas mitigation target compared to previous submissions and identifies the waste sector as a priority mitigation area, emphasizing waste reduction, recycling, organic waste treatment, and methane mitigation from disposal sites and wastewater systems (Ministry of Environment, 2025). While NDC 3.0 provides clearer mitigation directions and indicative actions for the waste sector, it does not specify technology- or pathway-specific quantitative targets. Therefore, scenario-based modeling is required to translate these policy commitments into explicit treatment shares and mitigation potentials, as implemented in this study.

The BaU scenario treatment shares (Tables 4 and 5) were derived from: (1) current observed practices in Cambodia (limited formal recycling, near-total reliance on open disposal); (2) regional trends in comparable lower-middle-income countries; and (3) national waste management objectives. The CM scenario shares were informed by: (1) realistic implementation bounds given current infrastructure; (2) NDC 3.0 guidance (Ministry of Environment, 2025); and (3) analogous ExSS/Waste model targets for Vietnam and Malaysia (Nguyen and Matsuoka, 2017; Siong et al., 2013). Expert judgment balanced policy ambition against technical feasibility.

Targets of solid waste treatment developed by the model are based on actual and current measures applied in the world including composting, recycling, incineration, and disposal.

Based on targets of waste management in Cambodia and components of waste in different sectors, estimations of specific target for each treatment measures applied in each sector are shown in Table 4 and Table 5.

Table 4. Estimation of composition of solid waste management in BaU and CM

Sector	Waste type	Management	BaU			CM	
			2010	2030	2050	2030	2050
Residential and commercial	Paper, textile, nappies, plastic, etc.	Recycling	0.01	0.10	0.30	0.30	0.70
		Incineration	0.00	0.01	0.04	0.05	0.10
		Composting	0.00	0.00	0.00	0.00	0.00
		Disposal	0.99	0.89	0.66	0.65	0.20
	Food, garden, wood, etc.	Recycling	0.01	0.10	0.30	0.10	0.20
		Incineration	0.00	0.01	0.04	0.05	0.10
		Composting	0.00	0.10	0.40	0.30	0.50
		Disposal	0.99	0.79	0.26	0.55	0.20
	Others (metal, glass, brick, concrete, etc.)	Recycling	0.01	0.10	0.30	0.30	0.70
		Incineration	0.00	0.00	0.00	0.00	0.00
		Composting	0.00	0.00	0.00	0.00	0.00
		Disposal	0.99	0.90	0.70	0.70	0.30
Industrial	Others	Recycling	0.10	0.20	0.50	0.30	0.70
		Incineration	0.00	0.01	0.04	0.05	0.10
		Composting	0.00	0.00	0.00	0.00	0.00
		Disposal	0.90	0.79	0.46	0.65	0.20
Construction	Wood, brick, soil, concrete, etc.	Recycling	0.10	0.20	0.50	0.30	0.70
		Incineration	0.00	0.00	0.00	0.00	0.00
		Composting	0.00	0.00	0.00	0.00	0.00
		Disposal	0.90	0.80	0.50	0.70	0.30

Table 5. Estimation of composition of wastewater management in BaU and CM

Sector	Management option	BaU	CM	
		2010-2050	2030	2050
Residential wastewater	Non-treated	0.80	0.20	0.00
	Treated	0.20	0.80	1.00
Industrial wastewater	Non-treated	0.60	0.25	0.00
	Treated	0.40	0.75	1.00

2.4.4 Methane (CH_4) recovery

At present, there are no targets for collecting CH_4 from waste in Cambodia from disposal sites and wastewater. In the BaU scenario, there is no CH_4 colleting system in 2010, and only 1% and 5% of CH_4 are expected to collect in years 2030 and 2050, respectively. In the CM scenario, we assumed, there will be 5% and 20% collected from disposal sites and 5% and 20% collected from treated wastewater, respectively for the years 2030 and 2050.

3. RESULTS

In BaU scenario, GHG emissions increased from 1.6 $MtCO_2eq$ in 2010 to 5.7 in 2030 and 15.2 $MtCO_2eq$ in 2050. GHG emissions from the industrial sector are expected to continue to increase in importance due to rapid industrial expansion and to contribute the highest level of emissions accounting for more than 70% of the total emissions in the future (see Table 6). GHG emissions increase sharply in 2050 in the BaU scenario accounting for 15.2 $MtCO_2eq$.

Assuming a better waste management strategy and increased methane recovery, GHG emissions can be reduced 13% in 2030 and 39% in 2050.

The rapid BaU emissions increase is driven primarily by industrial output growth (amplifying industrial solid waste and landfill methane) and urbanization. The limited 2030 reduction versus 2050 reflects the FOD time-lag: methane from pre-scenario waste continues emitting for years. By 2050, cumulative recycling and methane capture benefits compound substantially, underscoring the importance of early policy intervention.

Among GHG, methane emission is the biggest emission source accounting for approximately 40% of total emissions from waste (see Figure 1).

From the disposal site, methane emitted from industrial waste accounts for the largest share compared to other waste types, as summarized in Table 7. The industrial methane contribution is projected to reach 3.36 $MtCO_2eq$ (total 4.33 $MtCO_2eq$ in 2030) and 4.54 $MtCO_2eq$ (total 5.95 $MtCO_2eq$ in 2050).

Table 6. GHG emissions by sector in BaU and CM scenarios ($MtCO_2eq$)

		Business-as-usual (BaU)			Countermeasure (CM)	
GHG Source	Sector	2010	2030	2050	2030	2050
CH_4 from disposal site	Residential	0.17	0.56	0.76	0.49	0.46
	Commercial	0.17	0.41	0.64	0.36	0.39
	Industrial	1.11	3.36	4.54	2.92	2.77
	Construction	0.000	0.010	0.010	0.010	0.010
	Sub-total	*1.46*	*4.33*	*5.95*	*3.77*	*3.63*
CH_4 from wastewater	Residential	0.0003	0.0019	0.0029	0.0017	0.0018
	Industrial	0.0001	0.0004	0.0014	0.0003	0.0009
	Sub-total	*0.0004*	*0.0023*	*0.0043*	*0.0020*	*0.0026*
Fossil CO_2 from incineration	Residential and Commercial	0.14	1.37	9.25	1.19	5.64
TOTAL		1.59	5.71	15.20	4.97	9.27

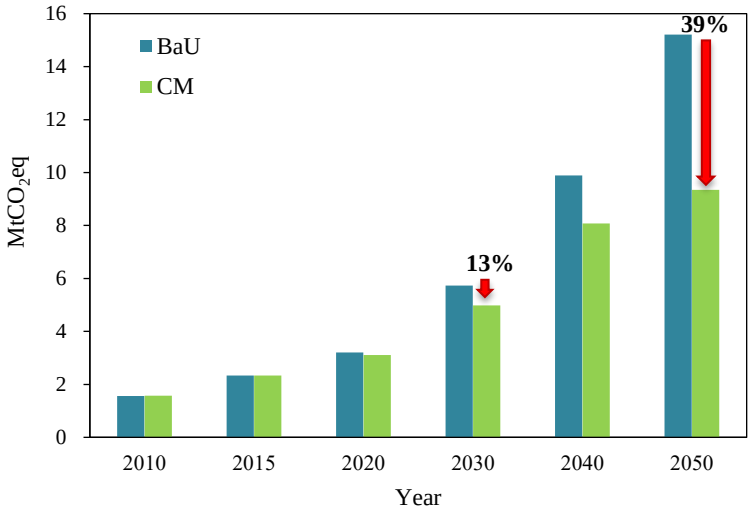


Figure 1. GHG emissions/reductions in BaU and CM scenarios in Cambodia

Table 7. Emission from disposal site in the period of 2010-2050

Methane from disposal site ($MtCO_2eq$)				
	2010	2030	2050	2030 (US EPA, 2012)
Residential	0.17	0.56	0.76	0.5
Commercial	0.17	0.41	0.64	
Industrial	1.11	3.36	4.54	
Construction	0.00	0.01	0.01	
Total	1.46	4.33	5.95	

US EPA (2012) has studied global mitigation of Non-CO_2 GHG in the period from 2010 to 2030 including Cambodia. It estimated methane from disposal sites from the residential sector in Cambodia in 2030 with a value of 0.5 $MtCO_2eq$. This number is quite similar to this study's estimation.

From wastewater treatment process, methane emission from residential wastewater is significantly greater than that from industrial wastewater in Cambodia (see Table 8).

4. DISCUSSION

4.1 Global climate and environmental benefits results from GHG emission reduction in waste sector

Efforts to reduce GHG emissions from the waste sector include reducing the amount of waste generation (recycling, recovery), improving the efficiency of waste collection, expanding methane avoidance (renewable energy replacing fossil fuel energy sources), and carbon bound in soil through compost application etc. These are key components of an integrated waste management strategy that would enable the waste sector to become a global net emissions saver.

Waste recycling receives the highest priority to reduce the amount of waste disposed, representing significant potential for reducing GHG emissions by conserving raw materials and fossil fuels. This is also the most favorable reduction option in Cambodia, accounting for approximately 77% of total reduction amount in 2050.

Waste offers a significant source of renewable energy. Through methane recovery, which accounted for 22% of the total GHG emissions reduction in 2050 in Cambodia, energy generated from methane combustion can displace other fossil fuels, either as a process energy resource or as electricity.

Table 8. Emission from wastewater in the period of 2010-2050

CH_4 from wastewater treatment ($MtCO_2eq$)				
	2010	2030	2050	2030 (US EPA, 2012)
Residential	0.0003	0.0019	0.0029	0.0
Industrial	0.0001	0.0004	0.0014	
Total	0.0004	0.0023	0.0043	

Note: In US EPA (2012), it estimated for residential waste only using Waste model in IPCC (2006), the activity data for population was referred to US Census database for countries that did not provide their own population data.

Through biological treatment, organic wastes (food waste, wood waste and garden waste) can be recovered and transformed into fertilizers. These processes reduce GHG emissions by sequestering carbon in soils and replenishing soil nutrients. Organic waste constitutes a large component of the waste stream, ranging from 30-70% of total residential and commercial waste (66% in Cambodia in 2010). Therefore, separate collection of the organic component of waste can offer a valuable contribution to GHG emission reduction and soil improvement.

There is a need to consider the environmental, economic, and social aspects of different waste management options in order to reduce GHG emissions. The assessment does not concentrate only on the amount of mitigated GHG, but also on regional conditions, such as the implementation feasibility of each option, direct and environmental costs, land availability, and so forth. The selected integrated system of waste management should deliver both economic and environmental sustainability.

The sound and strong policies and regulations of waste management are very important national drivers to reduce GHG emissions, especially in developing countries. Each country's initiatives cannot be exported to another country or region without taking into account local waste characteristics, infrastructure, climate and economic conditions. Governments have a range of policy options to encourage waste management practices that will reduce greenhouse gas emissions.

These findings are consistent with national-level assessments using the ExSS/Waste model in Vietnam and Malaysia, where recycling and methane recovery were also the dominant mitigation measures (Nguyen and Matsuoka, 2017; Siong et al., 2013). Compared to IPCC inventory-based approaches, the scenario-based ExSS/Waste model allows more explicit quantification of technology-specific mitigation pathways, providing actionable insights for national climate planning in developing countries.

4.2 Waste sector and GHG emissions in Cambodia and other Asian countries

Table 9 presents a comparison of municipal solid waste generation and associated GHG emissions across Cambodia and selected Asian countries for the year 2025. Waste generation amounts are estimated based on country-specific per capita generation rates and population data. Generation rates for Cambodia are derived from this study, while those for Vietnam, Malaysia, and Japan are taken from Nguyen and Matsuoka (2017), Siong et al. (2013), and Hoornweg and Bhada-Tata (2012), respectively; rates for the remaining countries are based on Nguyen and Schnitzer (2009).

Japan exhibits the highest per capita waste generation rate, followed by Singapore, Malaysia, and Indonesia, reflecting the higher income levels and consumption patterns. In contrast, Cambodia, the Philippines, Thailand, and Vietnam show relatively similar generation rates, ranging from 0.52 to 0.64 kg/capita/day. However, despite lower generation rates, Cambodia, Vietnam, Indonesia, and Malaysia, have a high organic fraction in municipal solid waste, exceeding 55%.

This high organic content is a key driver of elevated methane emissions from waste disposal, explaining why countries such as Vietnam, Indonesia, and Malaysia exhibit substantial GHG emissions from the waste sector (62.9, 73.3, and 61.0 $MtCO_2eq$, respectively). Although Cambodia remained at a lower level of economic development in 2025, its estimated waste-related GHG emissions are comparable to those of Japan and approximately double those of Singapore, primarily due to limited waste treatment infrastructure and reliance on disposal-based management. These findings highlight the significant mitigation potential in Cambodia's waste sector, and support the effectiveness of countermeasure scenarios that achieve emission reductions of 13% by 2030 and 39% by 2050 relative to the BaU scenario.

The results of this study are consistent with previous national-level assessments that applied the ExSS/Waste model in Southeast Asia. Similar to the findings reported for Vietnam and Malaysia, this study identifies recycling and methane recovery as the dominant mitigation measures, jointly accounting for more than 80% of total emission reductions by 2050 (Nguyen and Matsuoka, 2017; Siong et al., 2013). However, the relative mitigation potential in Cambodia is higher when expressed as a share of baseline emissions, reflecting the current dominance of disposal-based waste management and the high organic fraction of municipal solid waste.

Compared with studies based on the IPCC Waste Model, which primarily focus on inventory-level emission estimates, the ExSS/Waste approach applied in this study allows a more detailed assessment of technology-specific mitigation pathways under long-term scenarios. While IPCC-based estimates for several Asian countries report comparable absolute methane emissions from disposal sites, this study demonstrates that the early implementation of integrated waste management strategies in Cambodia could yield mitigation outcomes comparable to or greater than those observed in more economically advanced economies. These comparisons position Cambodia as a high-impact case for waste-sector mitigation in the region and highlight the contribution of this study as the third national application of the ExSS/Waste model.

4.3 Uncertainty and limitations

Several sources of uncertainty should be acknowledged. First, waste generation projections rely on income-based assumptions (Hoornweg and Bhada-Tata, 2012) that may not fully capture Cambodia-specific drivers. Second, industrial and construction waste composition data, rely on Vietnamese proxy values; given the predominantly inorganic nature of waste in these sectors, the impact on total GHG estimates is expected to be limited. Third, CM scenario treatment shares are based on expert consultation and regional analogies rather than bottom-up engineering feasibility assessments. Fourth, the model excludes GHG emissions from waste collection vehicles. Fifth, FOD parameters rely on IPCC default values that may deviate from actual Cambodian site conditions. Future work should address these limitations through field measurement campaigns and sensitivity analyses.

5. CONCLUSION

This study assessed future waste generation and GHG emissions in Cambodia for the period 2010-2050. The results indicate that total waste generation is projected to increase to approximately 10.1 million tons/year by 2030 and 34.1 million tons/year by 2050, corresponding to 3.5 and 11.7 times the 2010 level, respectively. Under the BaU scenario, total GHG emissions from the waste sector are estimated to rise from 1.6 $MtCO_2eq$ in 2010 to 5.7 $MtCO_2eq$ in 2030 and 15.2 $MtCO_2eq$ in 2050.

Table 9. Waste generation and GHG emissions in Cambodia and other Asian countries in 2025

Country	GDP per capita (USD)		Population		Waste generation rates (kg/cap/day)		Organic fraction in waste[e] (%)	GHG emissions ($MtCO_2eq$)	GHG emission estimation method
	2010[a]	2025[b]	Urban[c] (%)	Total[b] (million)	Generation rates (kg/cap/day)	Waste generation amount (tons/year)			
Cambodia	783	985	48.6	17.2	0.62[g]	3,884,666	55	4.3[g]/0.5[h]	ExSS/Waste Model[d]
Vietnam	1,334	2,010	39.0	93.4	0.61[d]	20,799,963	60	62.9[d]/10.3[h]	ExSS/Waste Model[d]
Philippines	2,136	2,691	74.3	107.7	0.52[c]	20,435,766	41	12.9[h]	IPCC Waste Model[i]
Indonesia	3,137	3,376	60.7	253.6	0.76[c]	70,351,414	62	73.3[h]	IPCC Waste Model[i]
Thailand	4,803	5,617	39.1	67.7	0.64[c]	15,824,064	48	10.6[h]	IPCC Waste Model[i]
Malaysia	8,754	11,204	72.7	30.1	0.81[c]	8,890,196	62	61.0[f]	ExSS/Waste Model[d]
Singapore	46,570	55,135	100.0	5.6	1.10[c]	2,236,355	44	2.1[h]	IPCC Waste Model[i]
Japan	42,909	37,530	100.0	127.1	1.70[e]	78,865,550	26	4.3[h]	IPCC Waste Model[i]

[a] GDP per capita. The World Bank. HP <http://data.worldbank.org/indicator/NY.GDP.PCAP.CD>

[b] List of Countries Forecast 2025. HP<http://www.deagel.com/country/forecast.aspx?pag=4&sort=Alphabetical&ord=DESC>

[c] Nguyen and Schnitzer (2009)

[d] Nguyen and Matsuoka (2017)

[e] Hoornweg and Bhada-Tata (2012)

[f] Siong et al. (2013)

[g] This study

[h] US EPA (2012)

[i] IPCC (2006)

Implementation of CM scenarios could reduce emissions by approximately 13% in 2030 and 39% in 2050 relative to BaU. Recycling is identified as the most effective mitigation option, accounting for about 60% and 77% of total GHG reductions in 2030 and 2050, respectively, while methane recovery represents the second most significant mitigation measure. A comparison with other Asian countries indicates that Cambodia's waste-sector emissions are relatively high in relation to its income level, largely due to the high organic fraction of waste and limited treatment capacity, highlighting substantial mitigation opportunities through improved waste management practices.

Overall, the findings demonstrate that low-carbon waste management strategies can substantially reduce GHG emissions while simultaneously improving waste management performance. The results provide quantitative evidence to support the formulation of sustainable and climate-oriented waste management policies in Cambodia. In practical terms, policymakers should prioritize investments in: separate collection infrastructure for recyclables; expansion of organic waste composting in urban centers; and installation of landfill gas capture systems at major disposal sites. Early action is critical, as delayed implementation locks in disposal-dominated emission trajectories. Future research should: (1) derive Cambodia-specific waste decay parameters through field measurement campaigns; (2) conduct cost-benefit analyses of CM scenario interventions; and (3) extend scenario analysis to additional mitigation pathways such as waste-to-energy and extended producer responsibility schemes.

ACKNOWLEDGEMENTS

The authors acknowledge the support received during the preparation of this manuscript. No external funding was received for this study.

AUTHOR CONTRIBUTIONS

Conceptualization, Thai-Huyen Nguyen and Kyoko Take; Data curation, Thai-Huyen Nguyen; Investigation, Thai-Huyen Nguyen; Resources, Thai-Huyen Nguyen; Writing and original draft, Thai-Huyen Nguyen; Methodology, Kyoko Take; Software, Kyoko Take; Formal analysis, Kyoko Take; Visualization, Kyoko Take; Validation, Thai-Huyen Nguyen and Kyoko Take; Writing-review and editing, Thai-Huyen Nguyen and Kyoko Take; Funding acquisition, not applicable.

DECLARATION OF CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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