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Original Research

Trajectory-Based Evaluation of Greenhouse Gas Mitigation Pathways in Municipal Solid Waste Systems: A System Dynamics Approach

Nattarat Phaingam, Phairat Usubharatana and Harnpon Phungrassami†

Department of Chemical Engineering, Thammasat School of Engineering, Faculty of Engineering, Thammasat University, Pathumthani, Thailand

†Corresponding author: Harnpon Phungrassami; pharnpon@engr.tu.ac.th

ORCID ID: 0009-0002-2930-5409 (Harnpon Phungrassami)

ORCID ID: 0009-0003-0158-6031 (Nattarat Phaingam)

ORCID ID: 0000-0003-3660-7421 (Phairat Usubharatana)

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ABSTRACT

Abstract: Municipal solid waste (MSW) management is a critical component of greenhouse gas (GHG) mitigation in landfill-dominated systems, where methane emissions are governed by cumulative waste deposition and delayed decomposition processes. Conventional assessments often emphasize end-state comparisons, which can obscure the long-term consequences of intervention timing, stock accumulation, and demand-driven non-linear dynamics. This study applies a system dynamics (SD) modeling framework to evaluate trajectory-based GHG mitigation pathways in Thailand's national MSW system over a multi-decadal horizon (2024-2050), with explicit consideration of methane legacy effects and tourism-driven variability in waste generation. The model represents MSW generation, waste routing, landfill stock accumulation, and delayed methane emissions using first-order decay logic. Tourism activity is incorporated as a time-varying external driver affecting waste generation flows, allowing demand fluctuations and non-linear responses to emerge without altering the underlying system structure. Four scenarios are analyzed to reflect alternative intervention timings and waste management pathways under a consistent modeling framework. Simulation results show that early intervention substantively reshapes emission trajectories by constraining landfill stock accumulation, which, within the defined system boundaries, acts as a critical leverage point for long-term mitigation. In contrast, delayed interventions, despite achieving similar diversion levels at later stages, retain substantially higher cumulative GHG emissions due to legacy effects embedded in previously accumulated waste. Tourism-driven increases in waste generation act as a stress amplifier, accelerating stock formation and magnifying emissions under landfill-dominant configurations, leading to disproportionate GHG responses relative to demand growth. Overall, the findings demonstrate that the performance of GHG mitigation in MSW systems is strongly shaped by path dependence, time delays, and non-linear demand dynamics. Trajectory-based analysis provides essential insight into why late-stage mitigation cannot fully reverse methane legacy effects, underscoring the importance of early structural change for achieving sustained emission reduction in landfill-dominated waste management systems.

INTRODUCTION

MSW management has emerged as a critical component of GHG mitigation strategies, particularly in countries where landfilling remains the dominant means of disposal. In such systems, methane emissions from landfills constitute a major share of waste-related GHG emissions due to the anaerobic decomposition of organic materials over extended periods (Chiemchaisri and Visvanathan 2008; Karak et al. 2012). Unlike combustion-based sources, landfill methane emissions are characterized by delayed release and prolonged persistence, creating long-term commitments to emissions that extend well beyond the time of waste disposal.

Conventional assessments of MSW-related GHG emissions often rely on static inventories or end-state comparisons, focusing on emissions in a single target year or under a final system configuration (Hoornweg and Bhada-Tata 2012). While such approaches are useful for benchmarking and reporting purposes, they are limited in their ability to capture the dynamic behavior of landfill-dominated systems. In particular, static assessments tend to obscure the effects of stock accumulation, time delays in methane generation, and the path-dependent nature of emission trajectories, where past waste management decisions constrain future mitigation potential.

The importance of accounting for temporal dynamics in landfill methane emissions has been widely recognized in methodological frameworks based on first-order decay (FOD) logic, such as those adopted in national GHG inventories. These frameworks explicitly link current and future methane emissions to historically accumulated waste stocks rather than solely to contemporaneous waste flows. As a result, reductions in waste generation or diversion rates implemented at later stages may have limited influence on cumulative emissions that are already embedded in existing landfill stocks. This temporal asymmetry underscores the need for analytical approaches capable of tracing emission trajectories over extended time horizons, rather than relying on snapshot evaluations.

SD modeling provides a suitable framework for addressing these challenges, as it is specifically designed to represent accumulation processes, feedback mechanisms, and delayed responses in complex systems (Sterman 2018). SD has been increasingly applied in MSW studies to explore long-term system behavior, capacity constraints, and interactions among waste generation, treatment pathways, and infrastructure development. However, many existing applications focus on specific subsystems or management components, such as waste generation forecasting, collection logistics, and financial performance, without explicitly examining how delayed methane emissions shape cumulative GHG outcomes across alternative intervention timings.

In parallel, MSW systems in tourism-intensive economies face additional complexity due to demand variability that is not directly proportional to resident population growth. Empirical studies have demonstrated that tourism activity can significantly increase MSW generation, often exhibiting non-linear relationships driven by consumption patterns, seasonal concentration, and infrastructure saturation (Mateu-Sbert et al. 2013; Arbulú et al. 2015). In destinations with constrained diversion capacity, surges in waste generation associated with tourism may lead to disproportionate increases in landfill disposal and associated GHG emissions. Despite this, tourism-driven demand dynamics are rarely integrated into long-horizon GHG mitigation analyses of national MSW systems.

Thailand represents a relevant case for examining these interacting dynamics. The country combines a landfill-dominated MSW management structure with sustained growth in tourism activity, creating conditions under which delayed methane emissions and demand-driven non-linearities may jointly influence mitigation performance. While national strategies and waste management plans have articulated targets for improved disposal practices and increased diversion, the effectiveness of such measures depends not only on their stringency but also on their timing relative to the accumulation of landfill stocks.

Against this background, there remains a need for empirical evaluations of GHG mitigation pathways that bridge the gap between static national inventories and the dynamic realities of MSW systems (Dianati et al., 2021). In the context of Thailand, while national climate strategies articulate net zero targets for 2050, there are limited national-scale studies that simultaneously integrate long-term MSW emissions trajectories with the demand load from tourism. Therefore, this study contributes to the existing literature through the policy-analytical application of SD and the expansion of evaluative system boundaries. First, by leveraging the pathway-generating capabilities of SD and coupling them with First-Order Decay (FOD) mechanics, this study shifts the evaluative focus from static end-state targets to dynamic pathway dependency. This approach helps quantify the methane legacy accumulating in landfills during periods of delayed transition—a dynamic often obscured in conventional assessments (Scharff et al., 2024). Second, the study address boundary limitations in standard census-based waste inventories by incorporating the transient tourist population. Functioning as an exogenous demand driver, tourism adds an unaccounted mass to the system. By integrating this absolute load, the model reflects the physical mass constraints on diversion policies in tourism-dependent economies more comprehensively, without assuming disproportionate per-capita generation rates.

Accordingly, the objective of this study is to evaluate GHG mitigation pathways in Thailand's MSW management system by applying an SD framework that captures these temporal and boundary dynamics. Specifically, the study aims to (i) quantify how stock accumulation and delayed methane generation create a path-dependent methane legacy, (ii) assess how the timing of policy interventions influences cumulative GHG outcomes compared to static end-point targets, and (iii) analyze the additional absolute load imposed by the transient tourism population on landfill-dominated systems. By focusing on pathway dependency over a multi-decadal horizon, the study provides empirical insights into why delayed interventions may fail to offset the historical methane legacy, thereby informing the planning of early structural transitions.

2. MATERIALS AND METHODS

2.1. Model conceptualization and system boundary

This study applies an SD modeling framework to evaluate trajectory-based GHG mitigation pathways in Thailand's MSW management system. SD is particularly appropriate for this analysis because it explicitly represents stock accumulation, delayed responses, and feedback mechanisms that govern the long-term behavior of landfill-dominated waste systems (Sterman 2018). In such systems, methane emissions are not solely determined by contemporaneous waste flows but are strongly influenced by historically accumulated waste and time-lagged decomposition processes, resulting in long-term emission commitments.

The model is conceptualized at the national scale to represent Thailand's MSW system as an integrated entity. This system boundary encompasses total MSW generation and its allocation among major treatment pathways, with particular emphasis on landfilling and diversion-oriented options. Representation at the national scale is adopted to ensure consistency with available data sources and national waste management targets, while enabling analysis of cumulative GHG emissions arising from system-wide interactions rather than localized effects. Sub-national disaggregation is intentionally avoided, as excessive spatial detail may obscure the dominant stock-flow relationships that determine long-term emission trajectories in landfill-based systems.

The temporal scope of the analysis spans a multi-decadal horizon from 2024 to 2050, preceded by a historical period used for model calibration and behavioral verification. This extended time frame is necessary to capture the delayed nature of methane generation from landfilled waste and to evaluate path dependence arising from earlier waste management decisions. By moving beyond short planning horizons, the model distinguishes between short-term reductions in waste flows and long-term emission commitments embedded in accumulated landfill stocks.

Tourism activity is incorporated as a time-varying external driver influencing MSW generation rates. Thailand's role as a major tourism destination introduces demand fluctuations that are not proportional to resident population growth and vary over time. In the model structure, tourism affects waste generation flows but does not alter the structural definition of system stocks or treatment pathways. This formulation allows the analysis to examine how demand variability interacts with capacity constraints and waste routing decisions without conflating transient demand shocks with structural changes in the MSW system.

Within this conceptual framework, GHG emissions arise primarily from landfill-related processes characterized by delayed decomposition behavior. Therefore, methane generation is represented as a stock-dependent process governed by time delays rather than as an instantaneous response to waste inflows. This representation provides the structural basis for analyzing methane legacy effects and assessing why delayed interventions may be unable to offset cumulative emissions associated with earlier landfill reliance.

2.2. Model structure and governing equations

To ensure full model transaprency and reproducibility, the physical flows of MSW and the delayed methane generation were explicitily modeled using a system dynamics stock-flow structure. The inflow of waste directed to the landfill stock (W_{landfill}) is determined by the total MSW generated multipled by the explicit allocation fraction for each disposal method $_{j}$ (e.g., managed anaerobic, unmanged shallow dump). For the historical baseline, these fractions were directly parameterized using empirical national waste management data from the Pollution Control Department (PCD), while future trajectories were defined by scenario-specific policy tartets. This formulated in Eq. (1)

$$\boldsymbol{W_{landfill,j}(t) = MSW_{gen}(t) \times f_{disposal,j}(t)} \qquad \dots (1)$$

Where $f_{\text{disposal,j}}$ (t) represents the dynamic fraction of waste routed to the specific landfill management type j at time t.

For the methane generation function, folloing the 2006 IPCC guidelines, the accumulation and decomposition of decomposalble degradable organic carbon (DDOCm) for each waste fraction i is formulated as a differential equation governing the stock (Eq. 2), and the subsequent methane emission flow (Eq. 3).

$$\boldsymbol{\frac{d(DDOCm_i}{dt} = \left[W_{landfill}(t) \times Fraction_i \times DOC_i \times DOC_{f,i} \times MCF\right] - [k_i \times DDOCm_i(t)} \qquad \dots (2)$$

$$\boldsymbol{CH_4(t) = \sum_i (k_i \times DDOCm_i(t) \times F \times \frac{16}{12})} \qquad \dots (3)$$

Where DOC_i is the fraction of degradable organic carbon, $DOC_{f,i}$ is the fraction of DOC that can decompose under anaerobic conditions, MCF is the methane correction factor (set to 0.4 for unmanaged shallow dumps), k_i is the decay rate constant (yr^{-1}), and F is the fraction of CH_4 in landfill gas (0.5).

While the standard IPCC Tier 1 approach suggests a default DOC_f of 0.5 for all waste types, this study adopted a Tier 2 waste-specific approach utilizing country-specific parameters to ensure maxium accuracy under local conditions. Alighed with Thailnad's Fourth Biennial Update Report (BUR4) and the Thailand Greenhouse Gas Emission Inventory System (TGEIS), differentialted DOC_f values – specifically 0.7 for highly degradable food/garden waste and 0.1 for resistant wood–were applied. The parameters used in the simulation is summarized in Table 1.

Table 1: Key parameters for the First-Order-Decay (FOD) methane generation model.

Waste Fraction	**Degradable Organic Carbon (DOC)**	**Fraction of DOC Dissimilated (DOC_f)**	**Decay Rate Constant (k, yr^{-1})**
Food waste	0.15	0.70	0.400
Garden waste	0.20	0.70	0.170
Paper and cardboard	0.40	0.50	0.070
Wood	0.43	0.10	0.035
Textiles	0.24	0.50	0.070
Nappies	0.24	0.50	0.170
Rubber and leather	0.39	0.50	-
Plastics, Metal, Glass	0.00	0.00	-

Note: k and DOC values are based on IPCC (2006) defaults for tropical wet climates. DOC_f values incorporate country-specific data alighed with Thailand's BUR4 inventory methodology.

2.3. Data acquisition and model calibration

The SD model was parameterized and calibrated using officially reported national datasets and peer-reviewed studies that have been previously applied to Thailand's MSW system. Historical MSW generation data for the period 2014-2024 were obtained from the annual *Thailand Municipal Solid Waste Situation Reports* published by the Pollution Control Department (PCD), which provide consistent national-level records of total waste generation, treatment practices, and disposal pathways (PCD 2014-2024). These data were used to establish baseline waste generation trends and calibrate the aggregate growth behavior of the MSW system before scenario analysis.

Waste composition data were derived from the most recent national survey conducted by the PCD, which reported that organic waste constitutes nearly half of Thailand's MSW stream, followed by plastics, paper, and other fractions (PCD 2021). In the model, waste composition was assumed to remain constant over the simulation horizon, consistent with previous national-scale MSW modeling studies in Thailand (Pudcha et al. 2023a; Pudcha et al. 2023b). This assumption allows the analysis to focus on structural and temporal dynamics rather than compositional uncertainty.

Socioeconomic drivers influencing MSW generation were represented using population, economic activity, and tourism indicators. Population data were obtained from official national statistics, while tourism activity was represented using annual tourist arrival data published by the Ministry of Tourism and Sports. Tourism was explicitly included as a separate demand component to reflect Thailand's status as a major tourism destination, where visitor inflows significantly influence waste generation beyond resident population effects, as demonstrated in previous Thai case studies (Sakcharoen et al. 2023). In the SD structure, tourism affects MSW generation flows but does not alter the internal stock structure of the waste management system.

Parameters governing GHG emissions from MSW treatment and disposal pathways were adopted from a combination of IPCC guidelines and Thailand-specific studies. Methane emissions from landfills were estimated using first-order decay (FOD) logic consistent with the IPCC methodology (IPCC 2006), which links current emissions to historically accumulated waste stocks. Emission factors for non-landfill pathways, including composting, mechanical-biological treatment (MBT), incineration, and open burning, were drawn from peer-reviewed Thai studies and internationally recognized sources previously applied in Thailand (Menikpura et al. 2012; Menikpura et al. 2013; Nordahl et al. 2023).

Model calibration focused on reproducing the observed long-term behavior of Thailand's national MSW system rather than achieving exact year-by-year correspondence. Simulated MSW generation trajectories were compared with official PCD statistics for the periods 2014-2018 and 2022-2023, with the years affected by the COVID-19 pandemic treated separately due to structural disruptions in tourism and economic activity. Additional consistency checks were conducted by comparing simulated waste-sector GHG emissions with Thailand's official greenhouse gas inventory, which reported approximately 22.2 Mt CO_2e from the waste sector in 2022 (DCCE 2024). This calibration strategy follows established system dynamics practice, emphasizing reproduction of dominant system behavior driven by appropriate structural relationships rather than statistical curve fitting.

2.4. Causal loop and stock-flow structure

This study employs a causal loop and stock-flow representation to explicitly capture the dynamic mechanisms governing GHG emissions in Thailand's MSW management system. The model structure is designed to represent how waste generation, waste routing decisions, and landfill accumulation interact over time to produce delayed and path-dependent emission trajectories.

At the core of the system is the accumulation of landfilled waste as a stock variable. Inflows to this stock are determined by total MSW generation and the fraction of waste directed to landfilling, while outflows represent gradual decomposition processes rather than physical removal of waste. Methane emissions are generated as a function of this accumulated stock using first-order decay logic, reflecting the delayed release of methane over extended periods following disposal. As a result, current emission levels depend not only on present waste flows but also on historical waste accumulation.

The causal structure includes reinforcing and balancing feedback mechanisms that shape long-term system behavior. Growth in MSW generation increases landfill accumulation, which in turn commits future methane emissions through delayed decomposition. Diversion-oriented interventions, such as recycling, composting, and mechanical-biological treatment, act as balancing mechanisms by reducing inflows to the landfill stock. However, their effectiveness is constrained by the size of the existing stock, which continues to emit methane even after diversion rates increase.

Tourism activity is incorporated as an exogenous driver influencing MSW generation flows. Increases in tourist arrivals raise waste generation rates, thereby accelerating landfill accumulation when diversion capacity is limited. Under such conditions, the system exhibits non-linear behavior, where proportional increases in demand result in disproportionate increases in landfill inflows and associated GHG emissions. Importantly, tourism does not alter the internal feedback structure of the system but amplifies existing dynamics by increasing pressure on waste management pathways.

The stock-flow structure is held constant across all the scenarios examined in this study. Differences among scenarios arise solely from changes in the timing and magnitude of interventions affecting waste generation and routing trajectories. This structural consistency allows for direct comparison of emission trajectories under alternative pathways and isolates the effects of intervention timing from changes in system configuration. By maintaining a common causal structure, the model highlights how early and delayed interventions diverge in their ability to influence cumulative GHG emissions due to methane legacy effects embedded in accumulated landfill stocks.

2.5. Scenario design and implementation logic

Four scenarios are developed to examine how alternative waste management strategies and intervention timings influence GHG emission trajectories in Thailand's MSW system over the period 2025-2050. The scenarios are designed to span a range of strategic directions, from policy continuity to transformative change, while maintaining an identical stock-flow structure across all cases. Quantitative targets embedded in each scenario are treated as exogenous assumptions guiding waste generation and routing trajectories rather than as optimization outcomes.

An overview of the scenario logic and associated quantitative assumptions is summarized in Table ~~1~~ 2, which highlights differences in intervention timing, magnitude, and strategic intent without presenting model outputs. This table is intended to support the interpretation of the scenario structure prior to the presentation of the simulation results.

Table ~~1~~ 2: Summary of scenario design and quantitative assumptions.

Scenario	Strategic orientation	Timing of intervention	Waste generation assumption	Diversion / utilization target	Landfilling implication	GHG mitigation intent
BAU	Policy continuity (baseline)	No new intervention	Continues recent historical trend	Constant at recent average levels	Landfilling remains dominant	Reference trajectory
CPI	Current policy implementation	Gradual (mainly up to 2027)	Follows baseline growth	Utilization increases to ~36% by 2027; appropriate disposal reaches ~80%	Landfill inflow reduced after mid-2020s	Tests sufficiency of existing policy timing
CEM	Circular economy maximization	Progressive (to ~2035)	Reduced through sustained prevention efforts	Recycling and recovery reach ~65% by 2035	Landfilling reduced to <10% of MSW	Tests whether strong flow reduction overcomes stock inertia
OGM	Optimal GHG mitigation (upper bound)	Early and aggressive (from early simulation period)	Reduced via strong intervention	Maximum feasible diversion with high organic waste recovery	Rapid reduction in landfill inflow	Isolates effect of early action on cumulative emissions

The Business-as-Usual (BAU) scenario serves as a reference trajectory representing the continuation of recent MSW management practices. In this scenario, the proportions of MSW allocated to different treatment and disposal pathways remain constant at the average levels observed during the recent historical period, with no additional interventions introduced beyond those already in place. BAU provides a counterfactual baseline against which alternative trajectories are evaluated.

The Current Policy Implementation (CPI) scenario reflects the gradual implementation of Thailand’s National Action Plan on Waste Management (Phase II, 2022-2027) (PCD 2022). As summarized in Table ~~1~~ 2, this scenario assumes a progressive increase in MSW utilization to approximately 36% by 2027, alongside an improvement in appropriate disposal practices to around 80% over the same period. Beyond 2027, waste management practices are assumed to stabilize at these achieved levels. The CPI scenario is designed to examine whether the timing and ambition of currently announced policies are sufficient to alter long-term GHG emission trajectories once methane legacy effects from accumulated landfill stocks are taken into account.

The Circular Economy Maximization (CEM) scenario represents a more ambitious pathway benchmarked against international circular economy practices. Under this scenario, recycling and recovery rates increase progressively, reaching approximately 65% by 2035, while the share of MSW sent to landfills declines to less than 10%. These targets are aligned with the long-term sustainability frontiers established in the EU Waste Frame work Directive (2018/851/EU) and Landfill Directive (2018/850/EU), which serve as global benchmarks for transitioning toward a near-zero landfilling system (European Commission, 2023; Zero Waste Europe, 2020). The CEM scenario is included as an analytical case to test whether strong flow-based interventions, even when aligned with leading international benchmarks, can overcome the inertia imposed by existing landfill stocks.

The Optimal GHG Mitigation (OGM) scenario is a normative, upper-bound case designed to align the MSW sector with Thailand’s updated Nationally Determined Contribution (NDC), which targets a reduction in GHG emissions of approximately 40% by 2030 relative to the BAU trajectory (ONEP 2020). While the OGM scenario integrates the high-level ambitions of the National Solid Waste Management Action Plan 2022-2027 (PDC, 2022)−iincluding 100% plastic packaging recycling and intensified organic waste recovery−it is primarily intended as a technical potential simulation. This scenario assumes early and aggressive intervention, combining rapid reductions in landfill inflows with maximized organic waste diversion. Given the significant feasibility constraints in real world implementation−such as municipal budget limitations, high operational costs of advanced treatment technologies, and the necessity for massive behavioral shifts in waste segregation−the OGM scenario does not represent a recommended policy pathway. Instead, it serves as a benchmark to isolate the maximum theoretical effect of early action on cumulative emissions under idealized conditions.

Across all scenarios, performance is evaluated using trajectory-based indicators rather than end-year outcomes. Annual and cumulative GHG emissions are tracked to capture both short-term dynamics and long-term emission commitments associated with delayed methane generation from landfilled waste. This design allows direct comparison of early and delayed intervention pathways and highlights the role of path dependence in shaping mitigation outcomes within landfill-dominated MSW systems.

2.6. Sensitivity analysis

To evaluate the policy conclusions against inherent uncertainties, a sensitivity and elasticity analysis was conducted on three critical parameters identified as highly influential in the MSW sector. For waste-specific paramters, the analysis deliberately focused on the food waste fraction. This is methodologically justified as biodegradable and organic waste constitutes the most dominant component of Thailand's MSW, typically accounting for 45% to over 57% of the total waste stream (Jawjit et al. 2025; Sakcharoen et al. 2023), making it the primary driver of rapid landfill methane generation. The selection of parameters and their variation bounds were rigorously established based on international guidelines and Thailand's national policy context.

First, for the methane generation rate (k), the baseline value of 0.40 yr-1 reflects the default value for highly degradable food waste in tropical wet climates (IPCC, 2006). A variation range of ±10% was systematically applied to evaluate the model's structural sensitivity. This systematic variation fundamentally adheres to the Transparency, Accuracy, Consistency, Completeness, and Compariability (TACCC) principles emphasized in Thailand's Fourth Undate Report (ONEP, 2022). Second, regarding waste composition variability, a ±10% variation was applied to the degradable organic carbon (DOC) fraction of food waste (baseline 0.15). According to the IPCC methodology, a ±10% uncertainty band accurately reflects the acceptable margin of sampling error for country-specific waste characterization data (IPCC, 2006; Kornboonraksa et al. 2004). Finally, to account for implementation uncertainties regarding diversion efficiency, an absolute variation of ±5% was applied to the overarching policy targets (e.g. varying a 65% diversion target to 60% and 70%). This parameterization bounds the plausible policy overachievement or failure risks, aligning with the operational targets and risk assessments outlined in Thailand's National Solid Waste Management Action Plan Phase II, 2022-2027 (PCD, 2022).

3. RESULTS AND DISCUSSION

3.1. Model validation and baseline behavior

Validation in SD emphasizes whether a model reproduces observed behavioral regimes for appropriate structural reasons, rather than solely minimizing point-wise prediction error. This approach is suited for the comparative, trajectory-based analysis of accumulation dominated systems such as MSW management, (Sterman 2018; Barlas 1996). Accordingly, the waste-generation submodel was evaluated first because it governs the upstream mass flows that propagate to treatment allocation and long-lived methane accumulation.

To evaluate the model against historical records, the pre-COVID period (2014-2019) was used to asses baseline structural consistency under normal operating conditions. A comparison between the simulated MSW generation and the observed data yields a coefficient of determination (R^2) of approximately 0.54 and a mean absolute percentage error (MAPE) of about 1.2%. In causal-descriptive (white-box) models, this statistical profile is characteristic of simulations that prioritize internal structural fidelity and mass balance over purely correlation point-to-point accuracy (Piedrahita et al., 2025; Sterman, 2018). The moderate R^2 reflects phase-shift penalties caused by high-frequency measurement noise and reporting artifacts common in administrative data

(Jadeja et al., 2022). Conversely, the low MAPE confirms that the model accurately captures the overall systemic scale and structural magnitude, falling well within the acceptable threshold (typically <7%) established for recent MSW system dynamics models (Liu et al., 2023).

To isolate the endogenous dynamic trend from these short-term reporting artifacts, a centered three-year moving average was applied to the observed data (Figure 1). In the context of long-term behavioral modeling, this moving average serves as a signal extraction technique to identify the underlying growth regime rather than an attempt to artificially improve correlational fit. As demonstrated in recent MSW system dynamics applications, divergences at the point-to-point level are often non-systematic errors; thus, the primary objective is to capture the equivalent mean and structural trend rather than transient data cycles (Pinha and Sagawa, 2020).

Furthermore, the COVID-19 disruption during 2020–2021 is treated as an exogenous shock. Evaluating a model against such periods serves as an extreme condition test to verify boundary adequacy, rather than a strict predictive exercise. The results indicate that the model demonstrates directional alignment—capturing the contraction and subsequent recovery. This confirms that its internal feedback mechanisms respond logically to significant shifts in macroeconomic drivers, ensuring its suitability as a policy laboratory for long-term scenario evaluation.

Under stable drivers, the baseline exhibits persistent growth in MSW generation. When coupled with limited diversion capacity, this growth results in long-lived downstream impacts due to stock-and-flow inertia in disposal pathways. Establishing this baseline behavior provides a necessary reference for interpreting the scenario outcomes in subsequent sections, where differences arise from intervention timing and pathway choices.

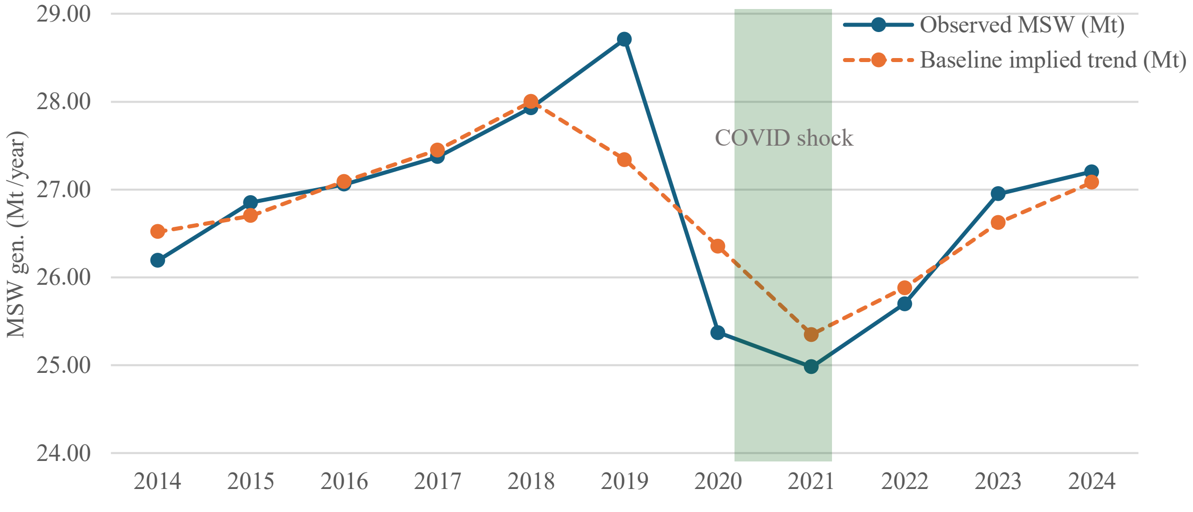

Fig. 1: Observed MSW generation and baseline implied trend in Thailand during 2014-2024.

Note: The baseline implied trend is derived from a centered three-year moving average of observed data to highlight dominant growth regimes and structural transitions rather than short-term fluctuations. The figure illustrates the pre-COVID growth regime (2014-2019), the COVID-19 disruption (2020-2021), and the subsequent recovery phase. For the pre-shock period, comparing the simulated outputs against the observed data yields a mean absolute percentage error (MAPE) of ≈1.2%, a maximum deviation of < 5%, and an $R^2 \approx 0.54$. These metrics reflect the model's representation of the overall systemic scale and long-term trajectory, establishing a behavioral reference for the subsequent comparative policy analysis.

3.2. Scenario-based GHG emission trajectories

Annual GHG emission trajectories from Thailand's MSW system were compared under BAU, CPI, CEM, and OGM over the assessment horizon, as shown in Figure 2. The BAU trajectory increases steadily toward 2050, rising from 16.2 Mt CO_2e in 2024 to 21.8 Mt CO_2e in 2050. This pattern is consistent with landfill-dominated systems in which delayed methane release from accumulated degradable carbon sustains emissions growth over time (Menikpura et al. 2013). CPI moderates emissions relative to BAU but does not reverse the long-run trajectory; by 2050, CPI remains at 15.9 Mt CO_2e, indicating that incremental improvements slow growth yet leave substantial legacy emissions in place (Table 3). This behavior reflects path dependence: when landfill inflows remain high during early years, methane-generating stocks persist even after diversion improves.

CEM and OGM exhibit qualitatively different trajectory shapes, with pronounced inflection beginning in the late 2020s. Emissions under CEM decline from 16.4 Mt CO_2e in 2025 to 11.8 Mt CO_2e in 2030 and approach 5.0 Mt CO_2e by 2050, while OGM declines more rapidly reaching 11.0 Mt CO_2e by 2030 and stabilizing at approximately 5.0 Mt CO_2e by 2050 (Table 3). Importantly, the mitigation advantage is explained by timing rather than end-state performance alone. Early constraints on landfill inflow—especially of organic fractions—prevent the formation of long-lived methane-generating stocks, producing disproportionate benefits that persist throughout the horizon. Conversely, delayed action yields diminishing marginal gains because previously accumulated waste continues to emit over extended periods, consistent with accumulation-dominated system behavior (IPCC 2019).

The trajectory-based interpretation is reinforced by the five-year snapshots in Table 3. While CEM and OGM converge toward similar end-state emission levels by 2050, their trajectories differ materially during the critical early years (late 2020s to mid-2030s), when stock formation is the most influential. CPI remains substantially higher than CEM/OGM across the horizon despite policy progress, demonstrating that mitigation effectiveness cannot be inferred from end-point indicators alone. This timing-driven divergence and robust ranking across the horizon align with findings from SD-based MSW studies that emphasize intervention timing and structural configuration over short-term prediction accuracy (Pinha and Sagawa 2020; Wang and You 2021). Therefore, extending assessment to 2050 is essential for net-zero-oriented interpretation in MSW systems: shorter horizons may capture near-term flow improvements but underrepresent legacy emissions from previously accumulated waste, which dominate long-run outcomes (Menikpura et al. 2013; IPCC 2019).

Despite the aggressive flow-based interventions simulated in the OGM scenario, the model indicates a residual emission gap of approximately 5 Mt CO_2e by 2050. This gap represents a residual baseline that requires downstream technological interventions to align with Thailand's Second Nationally Determined Contribution

(NDC 3.0), which has officially accelerated the national net zero emission targets to 2050 to remain consistent with the 1.5 °C pathway (DCCE, 2025). According to the prioritized investment framework in NDC 3.0, specific waste sector technologies are identified to close this gap, including Landfill Gas (LFG) Capture and Utilization (estimated mitigation potential of 1.00 Mt CO_{2e}), Organic Waste Composting and Decentralized Processing (0.50 Mt CO_{2e}), and Advanced Material Recovery Facilities (0.10 Mt CO_{2e}) (DCCE, 2025). These technologies, alongside other cross-sectoral measures, require an estimated additional investment of USD 0.94 billion by 2035 for the waste, industrial processes, and agriculture sectors.

Furthermore, addressing the hard-to-abate residual emissions necessitates the scaling up of negative emission technologies beyond standard solid waste management. Thailand's long-term strategy involves deploying Carbon Capture and Storage (CCS), with a specific target of 40 Mt CO_{2e} deployment in the power and energy sectors by 2050 (Thepsaskul et al., 2025). Ultimately, absolute economy wide neutrality will be achieved through a combination of Bioenergy with Carbon Capture and Storage (BECCS) and an ambitious national land-sink target of 120 Mt CO_{2e} sequestered via the LULUCF sector by 2050 (Waite et al., 2024; DCCE, 2025).

Additionally, while absolute emission levels vary with tourism demand assumptions, the relative ranking among the mitigation pathways remains consistent. Scenarios with earlier diversion yield lower emissions than delayed-action pathways under both high and low tourism growth conditions, indicating that the comparative effectiveness of these policies is not altered by uncertainties in tourism-driven waste generation. Beyond these demand-side factors, a quantitative sensitivity and elasticity analysis is provided in section 3.5 to assess how variations in key parameters (e.g., decay rates, waste composition, and implementation targets) affect the overall emission trajectories.

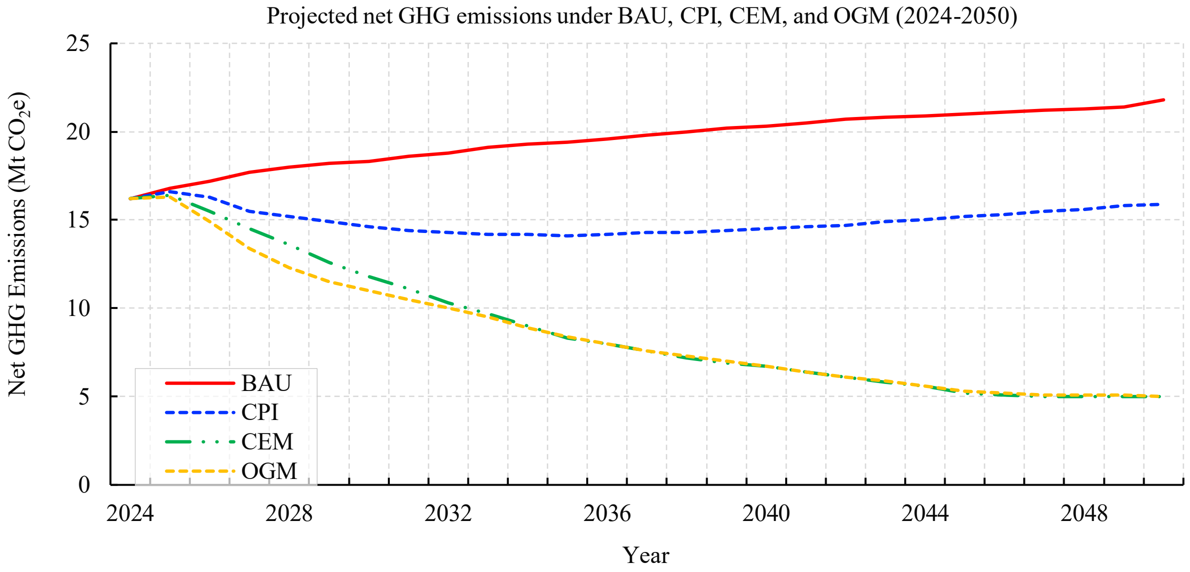

Fig. 2: Scenario-based GHG emission trajectories under BAU, CPI, CEM, and OGM (2024-2050).

(Note: Deterministic trajectories are presented here to emphasize structural pathway comparisons. For quantitative uncertainty ranges and parameter variability bounds, refer to the sensitivity analysis in Section 3.5.)

Table ~~2~~ 3: Annual GHG emissions under alternative MSW scenarios (Mt CO_2e yr^{-1}; five-year intervals).

Year	BAU	CPI	CEM	OGM
2025	16.8	16.6	16.4	16.3
2030	18.3	14.6	11.8	11.0
2035	19.4	14.1	8.3	8.4
2040	20.3	14.5	6.7	6.7
2045	21.0	15.2	5.2	5.3
2050	21.8	15.9	5.0	5.0

(Note: Values represent baseline discrete outputs under the standard deterministic assumption. Variability driven by parametric uncertainties are quantified in Section 3.5)

3.3. Tourism-driven non-linear dynamics in MSW-GHG trajectories

MSW generation in tourism-intensive systems cannot be adequately explained by resident population trends alone. Empirical studies consistently show that tourism activities introduce episodic, seasonal, and shock-sensitive waste inflows that are disproportionate to their annual average contribution (Mateu-Sbert et al. 2013; Arbulú et al. 2015; Sakcharoen et al. 2023). In the Thai context, tourism-related waste exhibits pronounced volatility associated with international arrivals, seasonal travel patterns, and exogenous shocks. This was the most notable during the COVID-19 period (Sakcharoen et al. 2023).

From a SD perspective, such demand components are characterized by high temporal clustering and elasticity, which causes them to interact differently with downstream waste-management processes compared with residential waste. While tourism-related MSW typically represents a minority share of annual waste quantities, its short-term surges can temporarily exceed diversion and treatment capacities, forcing excess flows toward landfill disposal pathways. This mechanism implies that tourism acts primarily as a stress amplifier rather than a dominant mass contributor within the MSW system.

In this study, tourism-driven waste generation is treated as an exogenous driver following a linear functional form, where total tourism MSW is the product of the tourist population and their specific per capita generation rate. However, the model aggregates tourist waste using a homogeneous national average. International and regional data suggest significant heterogeneity; for instance, luxury tourists or high-end resort guests can generate up to 3.5 kg/capita/day—substantially higher than the 0.8-1.7 kg/day typical of general visitors or residents (Kapmeier & Goncalves, 2018; Chuenwong et al., 2022). Consequently, if future tourism strategies increasingly prioritize high-end demographics, the current baseline—which uses a representative average for conservative estimation—might inherently underestimate the total waste volume.

Therefore, the described non-linear dynamics in this study do not stem from the demand function itself. Instead, they characterize the systemic feedback between episodic tourism-driven waste accumulation and strict landfill or diversion capacity constraints (Sterman, 2018). Although tourists contribute only a modest baseline share (~5-6%) of total MSW mass (Table 4), their seasonal surges act as a critical marginal load. When this marginal inflow temporarily exceeds available diversion capacities, the excess waste is structurally forced into landfill pathways. Because tourism-related waste often exhibits high organic intensity (e.g. concentrated food waste from hospitality sectors), this marginal load disproportionately amplifies the long-term methane legacy under anaerobic conditions (Sakcharoen et al., 2023). Addressing this systemic vulnerability requires active demand-side management; therefore, promoting low-waste tourism and source separation in the hospitality sector represent critical de-risking strategies for Thailand's net-zero ambitions.

Although tourism-related waste contributes a limited fraction of total annual MSW generation, its variability is substantially higher than that of residential waste. Table 4 summarizes representative years illustrating both the modest average share of tourism MSW and its pronounced sensitivity to demand shocks.

Table ~~3~~ 4: Contribution and variability of tourism-driven MSW.

Year	Total MSW (Mt)	Tourism MSW (Mt)	Tourism share (%)
2016	27.06	1.35	5.0
2018	27.93	1.62	5.8
2019	28.34	1.74	6.1
2020	24.98	0.62	2.5
2022	25.70	1.21	4.7

As shown in Table 4, tourism-driven MSW declined sharply during the COVID-19 disruption, followed by a partial recovery as tourism activity resumed. The relative contraction of tourism-related waste exceeded that observed for residential streams, consistent with empirical findings from tourism-dependent regions where visitor-related waste dominates short-term variability despite contributing a limited share of annual totals (Sakcharoen et al. 2023). This pattern highlights that annual-average waste shares are insufficient indicators of system stress. Periods of high tourism activity correspond to elevated peak inflows to disposal pathways, particularly when diversion and treatment capacities are constrained, thereby shaping downstream emissions outcomes.

The COVID-19 period provides a natural experiment for examining the interaction between tourism demand shocks and landfill dynamics. Model results indicate that tourism-driven MSW inflows respond almost immediately to changes in visitor activity, whereas landfill stocks and associated GHG emissions adjust much more slowly due to the stock-flow structure of landfill systems.

Figure 3 illustrates this asymmetric response by comparing indexed tourism MSW inflow, landfill accumulation, and GHG emissions. While tourism inflows exhibit sharp contractions and rebounds, landfill-related emissions remain relatively insensitive in the short term, as methane generation is governed by cumulative waste deposition and delayed degradation processes. The results demonstrate that even substantial short-term reductions in tourism waste fail to yield proportional decreases in emissions. Instead, tourism shocks primarily influence future cumulative emissions by altering landfill inflow trajectories, reinforcing the importance of methane legacy effects.

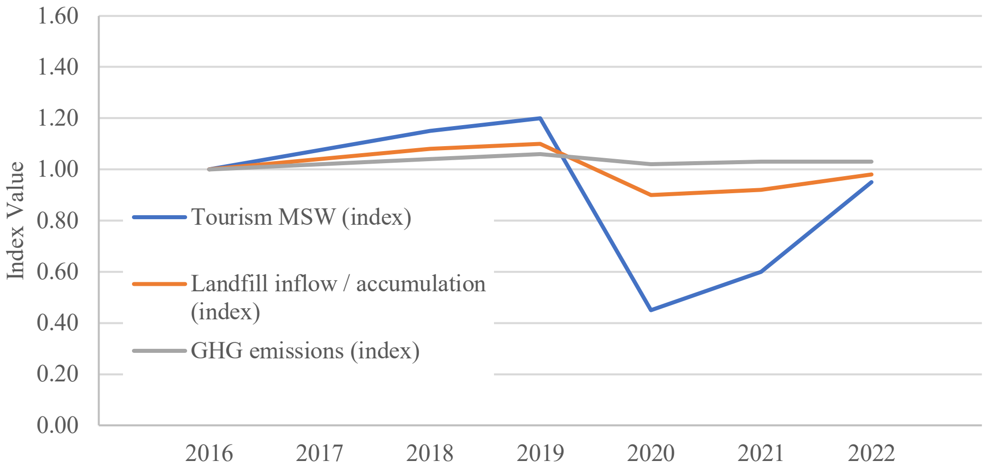

Fig. 3: Dynamic response of tourism-driven waste inflow, landfill accumulation, and GHG emissions (indexed).

(Note: The index value of 1.0 corresponds to the absolute baseline values in the reference year 2016 (i.e., MSW generation = 27.06 Mt yr^{-1}, Landfill inflow = 21.79 Mt yr^{-1}, and baseline GHG emissions = 16.12 Mt CO_{2e} yr^{-1}).

To assess how tourism variability interacts with alternative MSW management structures, a scenario-conditional sensitivity analysis was conducted. Tourism intensity was varied under fixed system configurations and resulting landfill inflows and GHG outcomes were compared across scenarios. Table 5 shows that landfill-dominant configurations exhibit strong sensitivity to tourism demand, with high tourism levels leading to disproportionate increases in landfill inflow and cumulative emissions. In contrast, scenarios characterized by early and sustained diversion capacity display a dampened response, indicating greater robustness to demand variability.

These differences reflect the structural properties of the system rather than parameter uncertainty. Thus, tourism functions as a diagnostic stressor that exposes the vulnerability of landfill-centric pathways and amplifies differences among mitigation strategies.

Table 5: Scenario-conditional sensitivity of GHG outcomes to tourism demand.

Scenario	Tourism level	Landfill inflow (Mt yr^{-1})	GHG emissions (index)
BAU	Low	22.4	0.96
BAU	High	25.1	1.08
High-diversion	Low	14.2	0.82
High-diversion	High	15.6	0.86

Taken together, the results indicate that tourism-driven waste dynamics influence GHG outcomes primarily through timing and routing effects rather than through annual waste volumes alone. Short-term tourism surges, even when followed by downturns, accelerate landfill stock accumulation, and commit the system to long-lived methane emissions due to delayed degradation processes.

This methane legacy effect explains why late-stage interventions cannot fully offset earlier landfill dependence and why mitigation performance is governed by emissions trajectories rather than end-state diversion targets. By integrating empirical tourism variability with SD modeling, the analysis demonstrates that robustness under variable and shock-prone demand conditions is a defining characteristic of low-emission MSW pathways in tourism-intensive systems.

3.4. Methane legacy effects and the long-term impact of delayed intervention

Landfill methane emissions are governed by the accumulation of biodegradable waste stocks and delayed anaerobic degradation processes rather than by contemporaneous disposal rates. Within the SD framework, landfill functions as a long-lived stock whose emissions evolve according to first-order decay behavior, implying that waste deposited in earlier periods continues to generate methane over extended time horizons. This structural characteristic creates a pronounced methane legacy effect, whereby present and future emissions are strongly conditioned by past disposal decisions rather than by current management performance alone.

The model results show that scenarios characterized by delayed diversion expansion accumulate substantially larger landfill stocks during early periods. Even when diversion rates subsequently converge toward more ambitious pathways, the emissions trajectories remain persistently higher because methane generation from previously deposited organic waste cannot be reversed. Therefore, late-stage interventions act primarily by slowing additional stock accumulation rather than by reducing emissions already committed through earlier landfill reliance. This explains why scenarios with similar end-state diversion shares can display markedly different cumulative GHG outcomes over the assessment horizon.

The dominance of timing over end-state performance reflects a form of path dependence intrinsic to landfill-based systems. Early landfill stock formation reinforces future methane generation through delayed feedbacks, widening divergence among scenarios as time progresses. Conversely, scenarios that introduce diversion earlier suppress the growth of landfill stocks during formative years, yielding long-term emissions benefits that persist even under comparable later-stage configurations. This timing effect is consistent with landfill-focused GHG studies emphasizing the importance of early waste routing decisions under first-order decay dynamics (Menikpura et al. 2013).

Importantly, the methane legacy effect also mediates the influence of demand variability. Short-term fluctuations in waste inflow—such as those driven by tourism dynamics—do not translate directly into proportional emissions changes. Instead, their long-run impact depends on whether marginal inflows are absorbed by landfill stocks during periods of constrained diversion capacity. When diversion is delayed, episodic inflow surges accelerate stock accumulation and persistently elevate cumulative emissions. When diversion is introduced earlier, the same variability yields attenuated long-term effects because marginal waste is structurally routed away from landfill pathways.

Taken together, these results demonstrate that GHG mitigation performance in municipal solid waste systems is governed by trajectory control rather than end-point optimization. The inability of late interventions to undo earlier emissions commitments highlights why mitigation assessments based solely on snapshot targets can be misleading. By explicitly representing time delays and stock-flow interactions, the SD framework reveals that early structural changes exert disproportionate influence on cumulative emissions outcomes, establishing methane legacy as a central determinant of long-horizon mitigation effectiveness.

Beyond affecting the timing and magnitude of municipal solid waste (MSW) inflows, tourism activity interacts with waste-management systems through characteristics commonly observed in urban and tourism-oriented contexts, particularly the prominence of organic waste fractions and disposable packaging in overall municipal waste streams. Studies in Thailand and other Southeast Asian cities indicate that food waste and packaging materials constitute a substantial share of municipal solid waste at the city level, reflecting consumption patterns associated with dense service activities, hospitality, and short-term consumption behavior (Vassanadumrongdee et al. 2018; Nguyen et al. 2015; Chuenwong et al. 2022). While these studies do not provide a direct source-specific comparison between tourism-related and household waste composition, they establish the relevance of waste composition as a determinant of downstream emission behavior in tourism-intensive urban systems.

From an SD perspective, waste composition influences GHG trajectories indirectly by shaping the effective emission characteristics of waste-treatment pathways rather than by altering total waste quantities alone. High organic content in municipal waste increases the methane generation potential when marginal waste is routed to landfill pathways, reinforcing long-term emissions through delayed anaerobic degradation. Conversely, a greater presence of packaging and composite materials affects the carbon intensity and mitigation performance of thermal treatment options. These mechanisms operate regardless of the precise origin of waste streams and are therefore relevant when tourism-driven inflows increase pressure on existing treatment capacity.

Tourism-driven waste generation is also inherently seasonal, characterized by sharp fluctuations between peak and off-peak periods. Such variability introduces transient stress on waste-management systems, particularly where diversion and treatment capacity expansion lags behind demand. Static and annual-average assessments tend to smooth out these fluctuations, potentially underestimating the risk that short-term inflow surges are absorbed disproportionately by landfill pathways. In contrast, the SD framework applied here captures how episodic demand peaks propagate through waste stocks and routing decisions, revealing sensitivity to both behavioral variability and infrastructure timing.

Simulation results indicate that under conditions of delayed diversion expansion, periods of elevated demand—whether tourism-related or otherwise—are more likely to translate into accelerated landfill stock accumulation. This effect arises not from waste composition alone, but from the interaction between inflow variability, pathway availability, and timing. Similar findings have been reported in SD-based waste studies, which emphasize that system robustness depends on structural flexibility and early pathway diversification rather than on average demand levels or end-state treatment shares (Wang and You 2021).

Taken together, waste composition characteristics and seasonal demand variability function as amplifying mechanisms within the MSW-GHG system. Tourism does not introduce a distinct emissions pathway through composition effects alone. Instead, it increases the likelihood that marginal waste is committed to long-lived landfill stocks during constrained periods. This interpretation reinforces the central conclusion that effective mitigation performance is governed by structural routing and timing, rather than by assumptions about waste composition differences between specific source categories. Additionally, the long-term sustainability of such pathways is further supported by community attitudes, which serve as a key driver for the success of decentralized facilities (Kisworo et al. 2025).

While ambitious diversion targets are assumed in the scenarios, implementation delays are inherently involved in realizing such systemic transitions. Real world behavioral shifts in household waste segregation are typically characterized by a non-linear S-curve adoption trajectory, which is consistent with established Diffusion of Innovation (DOI) theory (Rautan et al., 2025). Although the initial phase of public participation in waste sorting is often slow due to habit inertia, it has been demonstrated through empirical system dynamics modeling for Bangkok that recyclable waste can be comprehensively sorted within an approximated 17-year horizon, provided that active community engagement and structured policy support are implemented (Manasakunkit and Chinda, 2017). As the simulation commences in the 2024-2025 period, a 25-year window until 2050 is provided, which is considered a sufficient buffer for the behavioral S-curve to reach its stabilization phase.

Furthermore, the strategic importance of early action is heightened by this inherent lag time. Since methane generation in landfills is governed by first-order decay dynamics, the emission rate is determined by the cumulative stock of degradable organic carbon deposited in previous years (IPCC, 2006; Scharff et al., 2024). If diversion policies are delayed, more organic mass is structurally added to the landfill stock. Consequently, a long-term methane legacy is created, which is expected to continue emitting for decades even after behavioral norms have eventually shifted (Scharff et al., 2024). To accelerate this transition and minimize the lag phase, knowledge and subjective norms have been highlighted in recent Thai residential studies as the primary catalysts for stimulating waste separation intention (Pongpunpurt et al., 2022). By integrating these social drivers early in the policy roadmap, it is suggested that the acceleration phase of the S-curve can be optimized to meet the cumulative mitigation targets required for Thailand’s 2050 Net Zero ambition (Sakcharoen et al., 2023; Sunthara, 2025).

Despite the conceptual mechanisms discussed above, a notable structural assumption in this study is that the macroscopic waste composition was held constant over the simulation horizon. In practice, as upstream diversion policies (e.g., organic waste separation) mature, the fractional share of degradable organic carbon (DOC) routed to landfills will inherently decrease. This approach of assuming a constant composition is consistent with established system dynamics modeling practices for national-scale MSW analysis in Thailand (Pudcha et al., 2023). Since the baseline simulation maintains this constant composition, the methane abatement trajectories should be interpreted as conservative estimates (a lower-bound of policy benefits). However, the systemic response to such qualitative shifts was mathematically evaluated through the sensitivity analysis in Section 3.5. By varying the DOC parameter, which serves as a proxy for the organic fraction in the waste stream, the results demonstrate that qualitative improvements would further accelerate the mitigation of the methane legacy beyond the baseline projections. This confirms that early diversion not only reduces waste mass but also lowers the intrinsic emission potential of the residual stream.

While the current system dynamics framework primarily focuses on physical mass flows and GHG trajectories, the findings provide essential insights into the economic dimensions of MSW management. As outlined in Thailand's NDC 3.0 framework (DCCE, 2025), the deployment of downstream technologies required to abate residual emissions demands substantial capital investment, estimated at USD 0.94 billion by 2035 for the waste, industrial processes, and agriculture sectors. The model demonstrates that delayed intervention structurally locks in a larger methane legacy, which will inevitably increase future reliance on these capital-intensive solutions (Scharff et al., 2024). Based on national prioritization, these end-of-pipe measures carry significant abatement costs, such as USD 55.62/tCO_2 for landfill gas capture and USD 298.57/tCO_2 for advanced material recovery facilities (DCCE, 2025).

Conversely, early upstream diversion functions as a strategic cost-avoidance mechanism. By preventing the accumulation of degradable organic carbon in landfills through source separation, the financial burden associated with future technological remediation is substantially reduced. This is consistent with global assessments indicating that the long-term economic impact of environmental recovery can be multiple times higher than the cost of developing and operating proactive waste management systems (Kaza et al., 2018). Thus, it is suggested that evaluating mitigation pathways should not be limited to static abatement costs alone, but must incorporate the long-term financial liabilities and consequence cost savings generated by early policy action (Jadeja et al., 2022).

The mathematical convergence of annual emissions at approximately 5 Mt CO2e by 2050 across the intervention scenarios is a structurally bounded outcome driven by the predefined diversion targets. This convergence represents a physical floor of flow-based diversion measures, primarily consisting of unmanaged historical stocks and hard-to-abate residual waste (Waite et al., 2024). Nevertheless, the model's emergent behavior can be observed through its pathway dependency. While FOD mechanics indicate that early intervention yields greater mitigation (IPCC, 2006), the simulation quantifies the magnitude of the methane legacy accumulated during periods of delayed capacity expansion (Scharff et al., 2024). Furthermore, the elasticity assessment (Section 3.5) indicates that the long-term cumulative trajectory exhibits low sensitivity to variations in biological parameters (e.g., decay rates), whereas it remains strongly responsive to institutional enforcement and diversion efficiency (DCCE, 2025). This suggests that the system's overall mitigation performance is continuously shaped by implementation dynamics rather than being solely determined by the end-point targets.

3.5. Sensitivity and elasticity assessment

To validate the stability of the policy implications, the scenario-specific elasticity of cumulative GHG emissions (2024-2050) was computed against variations in critical parameters. As summarized in Table 6, the results reveal a profound structural dynamic, as scenarios become more ambitious in diversion targets, the system's sensitivity shifts fundamentally from biological parameters to institutional performance.

Table 6. Scenario-specific elasticity bounds of cumulative GHG emissions (2024-2050) to critical parameter variations.

Parameter	Variation tested	BAU	CPI	CEM	OGM
Methane generation rate (k)	±10% (0.36-0.44)	±0.45%	±0.45%	±0.45%	±0.45%
Degradable organic carbon (DOC) (food waste)	±10% (0.135 to 0.165)	±4.86%	±3.92%	±2.85%	±1.74%
Diversion efficiency	±5% (e.g., target ±5%)	±6.25%	±8.33%	±10.00%	±14.28%

First, the variation in the methane generation rate (k) consistently yields a negligible impact (±0.45%) on cumulative emissions across all scenarios. As established by the foundational mechanics of the First-Order Decay model (IPCC, 2006), the parameter k dictates the temporal distribution of emissions rather than the ultimate methane yield. Over the extended 26-year simulation horizon, highly degradable food fractions exhaust their ultimate methane potential regardless of minor decay rate fluctuations. Consequently, the long-term cumulative emission outcomes are mathematically bounded by the total landfilled mass, making the model highly against decay rate uncertainties. Second, an inverse sensitivity dynamic prominently emerges between waste composition (DOC) and diversion efficiency. Under the baseline pathway (BAU), cumulative emissions are highly sensitive to DOC variations (±4.86%) due to the continuous and dominant influx of unmanaged organic waste into disposal sites. However, as policy interventions intensify in the OGM scenario, organic waste is heavily diverted to alternative facilities (e.g., composting and MBT), thereby significantly suppressing the system's sensitivity to landfill DOC uncertainties (±1.74%). This phenomenon strongly aligns with recent empirical assessments demonstrating that circular economy interventions and bio-based solutions inherently de-risk landfill emission uncertainties by physically removing the organic source from the decay process (Jawjit et al., 2025; Sakcharoen et al., 2023).

Most critically, the model demonstrates that highly ambitious pathways (e.g., OGM) exhibit pronounced structural sensitivity to diversion efficiency targets (±14.28%). Because the baseline residual landfill input is substantially minimized in OGM, any absolute implementation failure (±5% target deviation) strictly results in a severe relative surge in cumulative emissions. This finding highlights a pivotal policy trade-off: while transitioning to advanced waste management scenarios significantly mitigates biological risks (e.g., DOC, k), it drastically elevates institutional and implementation risks. Therefore, ensuring strict adherence to the diversion targets through robust local enforcement is the most imperative factor in achieving the net-zero trajectory.

Finally, it is important to acknowledge the structural boundaries of the current SD model. The framework is specifically designed to evaluate physical mass-flow dynamics and their corresponding emission trajectories. While the implications of downstream technologies (such as landfill gas capture, flaring, or biological oxidation) and economic constraints (such as abatement costs and environmental liabilities) are critical, they are treated as external contextual factors rather than internal system variables. Therefore, the findings presented here should be interpreted as unmitigated, conservative upper-bound projections of physical pathway dependency, which must be integrated with broader techno-economic assessments for comprehensive policy planning.

4. CONCLUSIONS

This study employed an SD approach to examine the long-term GHG emission trajectories of MSW management under baseline growth, alternative mitigation pathways, and tourism-driven demand variability. By focusing on accumulation, time delays, and path dependence rather than point estimates or end-state outcomes, the analysis provides insight into how structural decisions shape cumulative emissions over a multi-decadal horizon. The results show that long-term GHG outcomes are governed primarily by trajectory-shaping mechanisms rather than by the eventual presence of waste-treatment technologies alone. Across all scenarios, early landfill stock accumulation emerged as a major structural determinant of cumulative emissions. Waste deposited during initial periods continues to generate methane over extended time horizons, creating a persistent emissions legacy that cannot be fully offset by delayed diversion or treatment expansion. As a result, scenarios that converged toward similar diversion levels at later stages still exhibited markedly different cumulative emissions, reflecting strong path dependence inherent in landfill-based systems. Scenario comparisons further demonstrate that the timing of structural intervention consistently outweighs the scale of late-stage mitigation efforts. Early diversion and reduced reliance on landfill pathways limit the formation of waste stocks and lead to substantially lower cumulative emissions, whereas delayed intervention locks in long-term methane generation, even with subsequent improvements in waste management performance. This finding indicates that mitigation effectiveness in MSW systems cannot be adequately evaluated using single-year emission levels, but instead requires trajectory- and cumulative-based assessment. Tourism-driven demand variability does not represent an independent mitigation pathway but functions as a stress amplifier that magnifies underlying structural differences among waste-management configurations. Systems with high landfill dependence exhibit pronounced sensitivity to demand fluctuations, as episodic increases in waste inflow translate directly into accelerated stock accumulation and higher cumulative emissions. In contrast, systems characterized by earlier diversion and pathway diversification display greater buffering capacity, maintaining more stable emission trajectories under variable demand conditions. Taken together, within the specific boundaries of upstream MSW management, the findings indicate that mitigating long-term methane emissions is heavily driven by controlling organic stock formation and feedback dominance, complementing the optimization of end-point technology deployment. Landfill-centered systems are governed by reinforcing feedbacks linking waste inflow, stock accumulation, and delayed methane generation, whereas diversified systems weaken such feedbacks by redirecting waste into pathways with different temporal emission profiles. The system dynamics framework is well-suited to reveal these mechanisms, which remain difficult to identify using static and accounting-based approaches. Although future waste demand—particularly that associated with tourism—remains uncertain, the structural patterns identified in this study suggest that early diversion and sustained reduction in landfill reliance consistently yield lower cumulative emissions across a wide range of plausible demand conditions. These insights underscore the importance of trajectory-oriented evaluation for understanding long-term mitigation performance in municipal solid waste systems.

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