

Modeling Thailand's Municipal Solid Waste Decarbonization: A System Dynamics Approach to Aligning MSW Management with NDC 3.0 and Net Zero 2050 Goals

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ABSTRACT

This study applied a System Dynamics (SD) model to simulate Municipal Solid Waste (MSW) generation and Greenhouse Gas (GHG) emissions in Thailand through to 2050. Calibrated with 2008-2024 data, the model uniquely incorporated tourism-related demand shocks and post-COVID recovery patterns alongside population, GDP, and urbanization drivers. Four scenarios were evaluated: Baseline Dynamic (BD), National Roadmap (NR), Circular Resilience (CR), and Net Zero Alignment (NZA). The results indicate that under BD, emissions reach 19.9 Mt CO₂e by 2050, failing national climate targets. Meanwhile, NR moderates growth (16.4 Mt CO₂e) and only CR (6.5 Mt CO₂e) and NZA (4.6 Mt CO₂e) achieve substantial reductions. Notably, the NZA scenario demonstrated alignment with Thailand's ambitious NDC 3.0 target of a 47% reduction by 2035. Landfill diversion of biodegradable waste was identified as the primary leverage point, minimizing methane generation at the source. This research provides a strategic framework to synchronize circular economy policies with explicit decarbonization objectives, supporting Thailand's transition toward Net Zero 2050.

Keywords-Municipal Solid Waste (MSW); Greenhouse Gas (GHG) emissions; System Dynamics (SD); decarbonization; Thailand NDC 3.0

I. INTRODUCTION

Municipal Solid Waste (MSW) management is a crucial global challenge, acting as a reservoir for resource recovery as well as a substantial source of Greenhouse Gas (GHG) emissions. This environmental issue has rapidly escalated into a severe socio-economic crisis, compelling nations to adopt rigorous decarbonization frameworks. As one of the "Most Affected Countries" globally and highly vulnerable to climate change, Thailand has significantly accelerated its climate ambition to address these threats [1]. In its latest Nationally Determined Contribution (NDC 3.0), submitted to the

UNFCCC in October 2025, Thailand transitioned from relative-to-Business-As-Usual (BAU) targets to an economy-wide absolute emission reduction target of 47% by 2035 (relative to the 2019 baseline), establishing a concrete trajectory toward its Net Zero 2050 goal [2]. This paradigm shift places unprecedented pressure on the MSW sector, which, despite being a minor contributor in absolute terms compared to the energy sector, possesses a high Global Warming Potential (GWP) due to methane emissions from open dumping and improper disposal practices that are prevalent in developing economies [3]. Globally, the waste sector

contributes approximately 5% of anthropogenic GHG emissions, primarily in the form of methane generated from landfills [4]. With rapid urbanization and increasing consumption, developing countries face significant challenges in sustainably managing growing waste volumes [3]. Thailand exemplifies these issues, generating approximately 26.95 Mt of MSW in 2024 [5], with its composition being dominated by organic matter (~49%), followed by Plastics (PT) and paper. Consequently, landfilling remains the primary disposal method, contributing significantly to national GHG emissions, which were reported to be approximately 9.99 Mt CO₂e in 2022 [6].

Despite the stringency of these mandates, existing literature on waste management in Thailand remains constrained by two critical methodological limitations. First, prominent forecasting studies, such as the Grey Modeling approach, predominantly rely on linear extrapolations of historical datasets (2011-2018) [7]. Multiple linear regression has also been applied to forecast MSW generation at the national level by modeling linear relationships between socio-economic drivers and waste generation [8]. While Artificial Neural Network (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS) approaches have been explored in local-scale applications to capture more complex or nonlinear relationships [9, 10], their predictive performance depends strongly on data sufficiency and model specification [10]. These forecasting-oriented approaches are useful for trend estimation, but such models have limited ability to evaluate how waste-management policies perform under feedback, delays, and structural change over time. In this context, System Dynamics (SD) offers a more appropriate framework for analyzing long-term policy interventions in waste-management systems. In Thailand, however, existing SD applications in MSW management have remained largely confined to Bangkok-based urban systems. Previous studies have applied SD to examine source separation, collection and transport efficiency, landfill life, and stakeholder interactions within Bangkok's recycling system [11, 12]. The value of SD is demonstrated for representing dynamic waste-management behavior and testing policy responses in urban settings [13]; though, their analytical scope remains limited to city-specific operational conditions. The present study extends SD-based analysis to the national scale, enabling the assessment of long-term decarbonization pathways for Thailand's MSW sector under broader socio-economic drivers and policy scenarios.

The second limitation in the Thai literature is the restricted incorporation of tourism as an explicit driver of MSW generation, particularly in relation to demand shocks during and after the COVID-19 period. This gap is particularly important because tourism influences solid waste generation in destination economies through visitor-related consumption and increased waste-management burdens [14, 15].

These traditional approaches do not fully capture the non-linear disruptions introduced by the COVID-19 pandemic and the subsequent "V-shaped" tourism recovery, in which international arrivals rebounded to 28.2 million in 2023 [16] and are projected to exceed 36.7 million in 2026 [17], creating a "demand shock" that static models cannot account for. Second, while the IPCC First-Order Decay (FOD) model typically requires long-term historical data (e.g., >50 years) to

estimate accumulated methane stocks, such extensive records are unavailable in the Thai context. Unlike previous studies that rely on short-term datasets (e.g., starting from 2011) without verifying their adequacy, this study extends the historical baseline to 2008 and explicitly validates the sufficiency of this dataset against observed landfill capacity constraints.

This research addresses these gaps by applying an SD approach to simulate Thailand's MSW generation and GHG emissions through to 2050, extending previous city-scale SD applications to the national level. By explicitly incorporating tourism-driven demand shocks and post-COVID recovery dynamics during 2020-2024, the model provides a stronger basis for analyzing long-term decarbonization pathways in Thailand's waste sector. Four distinct scenarios are evaluated: A Baseline Dynamic (BD), the existing National Roadmap (NR), and two high-ambition pathways-Circular Resilience (CR) and Net Zero Alignment (NZA).

The primary objective of this study is to quantify the GHG mitigation potential of these pathways and identify the specific leverage points - such as organic waste diversion and recycling allocation - necessary to align the MSW sector with Thailand's climate commitments. By integrating dynamic forecasting with emission scenario analysis, this research provides policymakers with a scientific basis for prioritizing investments and regulatory measures to bridge the gap between current practices and a net-zero-aligned future.

II. METHODOLOGY

A. System Dynamics Framework and Boundaries

An SD framework was applied in this research to model Thailand's national MSW management system and quantify GHG emissions until 2050. The SD approach was selected because it can explicitly account for feedback mechanisms, delays, and non-linear relationships governing system behavior, which are critical for capturing the complexity of waste management dynamics [18]. The model integrates four key exogenous socio-economic drivers: population, Gross Domestic Product (GDP), urban population share, and tourism. While population and GDP determine long-term growth trends, urbanization captures structural consumption patterns [19]. Notably, this study incorporates tourism to reflect external demand shocks, specifically addressing the seasonal fluctuations and the severe disruptions caused during and since the COVID-19 pandemic. The model accounts for the phased recovery of the tourism sector rather than assuming an immediate return to pre-pandemic conditions [20, 21].

Developed using Vensim PLE 10.4.0 [22], the proposed model operated on an annual time step from 2008 to 2050. A stock-flow structure was utilized to assess landfill-related emissions, as GHG generation represents the cumulative outcome of waste degradation over time. Although IPCC guidelines propose utilizing historical data spanning 50 years [23], this assessment relied on consistent national statistics that are only available from 2008 onwards [24], acknowledging this as a boundary constraint while ensuring structural validity through causal loop integration for other management pathways. The overall architecture of the SD model is

illustrated in Figure 1. The framework consists of four interconnected subsystems:

- Socio-economic drivers
- MSW generation
- Waste management pathways
- GHG emissions

The SD model was implemented using a stock-flow structure combined with causal relationships to represent the dynamics of waste generation, management pathway, and GHG emissions. Socio-economic drivers, including population, GDP per capita, urbanization rate, and tourism, acted as exogenous inputs that determine annual MSW generation through the regression-based generation module. The generated waste was subsequently routed through a management allocation module that distributes waste flows into different treatment and disposal pathways according to scenario-specific parameters.

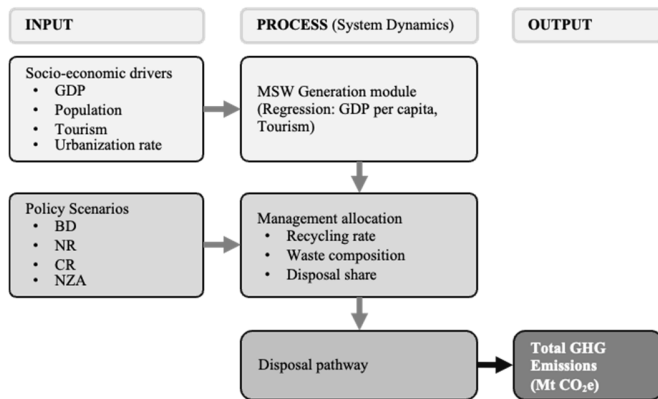


Fig. 1. Conceptual framework of the study.

B. Data Sources and Variable Selection

This study relied on secondary data compiled from authoritative national sources covering the period 2008-2024. Historical statistics on MSW generation, waste composition, and disposal pathways were obtained from the Pollution Control Department (PCD) [5, 24-33].

To identify the key drivers of MSW generation, a set of candidate demographic, economic, urbanization, and tourism-related variables was assessed. The variable-selection and model-specification procedure adopted in this study was consistent with approaches reported in the literature. For example, authors in [34] considered predictor significance, model fit, and multicollinearity when selecting parsimonious forecasting models. Similarly, in [35], model specifications exhibiting high multicollinearity were excluded and alternative models using adjusted R^2 , p -values, and additional model-fit criteria were compared. In [36], statistically significant predictors were retained after stepwise regression while screening multicollinearity using the Variance Inflation Factor (VIF). Following the same general logic, the present study evaluated candidate model specifications using three criteria: multicollinearity, explanatory performance, and statistical significance. Multicollinearity was assessed using the VIF, and

values greater than 10 were considered indicative of severe multicollinearity [35]. Explanatory performance was then estimated by comparing R^2 only among specifications that satisfied the multicollinearity criterion, with higher- R^2 models preferred provided that statistical significance was also satisfied. Statistical relevance was ensured by retaining only predictors with p -values < 0.05 at the 95% confidence level.

The six candidate model specifications were constructed through a structured variable-screening process to evaluate alternative socio-economic representations of waste generation. The initial specification included four potential explanatory variables: population, GDP, tourism, and the percentage of urban population, representing demographic, economic, and urbanization-related influences commonly associated with MSW generation. Alternative specifications were then tested by systematically removing selected predictors in order to examine model robustness and reduce potential multicollinearity. In this process, population and GDP were treated as core explanatory variables because previous studies have consistently identified demographic and economic factors as having a strong relationship with MSW generation in Thailand [7, 37]. Accordingly, these variables were retained as the principal ones during model development. An alternative economic specification was also examined by replacing the separate consideration of population and GDP with GDP per capita, which captures income effects normalized by population size [38, 39]. This allowed the analysis to test whether economic intensity provides a more parsimonious representation of consumption-driven waste generation. The resulting six candidate models therefore represent alternative demographic-economic configurations assessed before selecting the final specification.

TABLE I. DATA SOURCES AND DEFINITIONS OF CANDIDATE EXPLANATORY VARIABLES

Variables	Unit	Data sources
Tourism	persons	[27]
%urban population	%	[40]
Population	persons	[41]
GDP	US\$	[42]
GDP per capita	PPP constant 2021 international \$	[26]

TABLE II. CANDIDATE MODEL SPECIFICATIONS AND SELECTION CRITERIA

Model	Variables	VIF	R^2	p -value	Decision
M1	tourism	1.36	0.95	<0.005	Reject
	%urban population	11.33		0.28	
	population	7.83		0.02	
	GDP	13.07		0.22	
M2	Tourism	1.17	0.94	<0.005	Reject
	Population	7.10		0.03	
	GDP	6.73		0.49	
M3	%Urban population	9.75	0.68	0.09	Reject
	Population	6.93		0.03	
	GDP	12.65		0.27	
M4	Tourism	2.78	0.91	<0.005	Reject
	%Urban population	29.74		0.61	
	GDP per capita	34.03		0.15	
M5	GDP per capita	1.18	0.91	<0.005	Select
	Tourism	1.18		<0.005	
M6	%Urban population	12.66	0.79	<0.005	Reject
	GDP per capita	12.66		<0.005	

The variables, including tourism, %urban population, population, and GDP, were compiled from authoritative sources (Table I), while GDP per capita was additionally considered as an alternative economic indicator. The screening outcomes are summarized in Table II. Based on this integrated screening procedure, Model M5, which includes GDP per capita and tourist arrivals, was selected and subsequently embedded in the SD model as the MSW generation module. This specification was selected because it satisfied all three selection criteria, with acceptable multicollinearity, strong explanatory performance, and statistically significant coefficients.

C. MSW Generation Module

The resulting regression estimates were integrated as a data-driven input module within the SD framework. The structural dynamics of this subsystem were modeled through a stock-and-flow structure, as illustrated in Figure 2. In this structure, GDP per capita was defined as a stock (state variable) accumulated through economic growth rates, while tourism functions as an exogenous variable. These inputs collectively determined the total MSW generation through the derived regression coefficients (β), calculating MSW as an auxiliary variable at each time step through:

$$MSW_t = \beta_0 + \beta_1(\ln(GDP\ per\ capita_t)) + \beta_2(Tourism_t) + \epsilon_t \tag{1}$$

where MSW_t is the total MSW generation in year t (tons), $GDP\ per\ capita_t$ is the GDP per capita (PPP constant 2021 international \$), $Tourism_t$ is the number of tourist arrivals (persons), β_0 is the intercept, β_1 , β_2 are the regression coefficients, and ϵ_t is the error term.

Model adequacy was assessed using the coefficient of determination (R^2) and adjusted R^2 , while Analysis of Variance (ANOVA) was applied to test the overall model significance. Individual regression coefficients were evaluated using t -tests at a 95% confidence level.

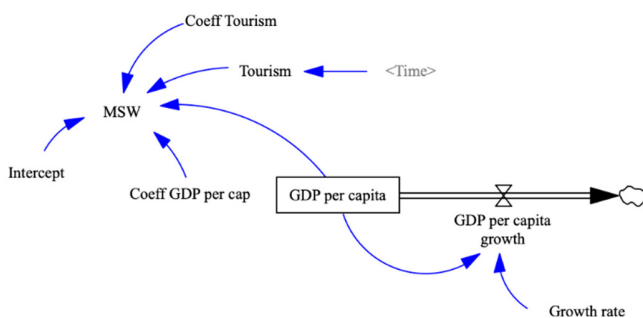


Fig. 2. Stock and flow diagram of the MSW generation sector, illustrating the dynamic link between economic growth (stock) and waste generation.

The regression module functioned not as a standalone forecasting tool, but as a data-driven input mechanism embedded within the SD framework. Its primary objective is to capture the structural relationship between waste generation and socio-economic drivers to facilitate long-term policy

scenario analysis, prioritizing structural validity and trend consistency over short-term point prediction accuracy.

D. Waste Management and GHG Calculation

GHG emissions were estimated following the methodologies and equations provided in the 2006 IPCC Guidelines and the 2019 Refinement [23, 43]. To ensure alignment with Thailand’s NDC 3.0 reporting standards, Global Warming Potential (GWP) values were adopted from the IPCC Fifth Assessment Report (AR5). This was consistent with Thailand’s national inventory framework [6], which excluded avoided emissions from recycling or energy recovery.

Within this accounting framework, waste flows were categorized into eight IPCC-aligned pathways based on national reports (2008-2024), covering anaerobic landfill, semi-aerobic landfill, unmanaged deep landfill, unmanaged shallow landfill, Composting (CO), Biogas Recovery (BO), incineration, and open burning. For intermediate technologies like MBT, RDF, and WtE, emissions were attributed solely to the residual fractions entering final disposal [44].

To govern flow dynamics, a waste suitability-based allocation matrix was established to distribute waste components to technically appropriate pathways (Table III).

TABLE III. WASTE SUITABILITY-BASED ALLOCATION MATRIX FOR MSW COMPONENTS.

Waste component	Controlled waste management	Uncontrolled waste disposal	Household-level waste management
PT	R / MWR / I	OB	HH-OB
Glass (GL)	R / MA / MS	UD / US	HH-US
Metal (MT)	R / MA / MS	UD / US	HH-US
Paper and Cardboard (PC)	R / MWR / I / CO / MA / MS	OB / UD / US	HH-OB / HH-US
Food Waste (FW)	BO / CO / MA / MS	UD / US	HH-US
Garden Waste (GW)	CO / BO / MA / MS / MWR / I	UD / US / OB	HH-OB / HH-US
Wood (WD)	R / MWR / I / CO / MA / MS	UD / US / OB	HH-OB / HH-US
Textiles (TX)	R / MWR / I / MA / MS	UD / US / OB	HH-OB / HH-US
Rubber and Leather (RL)	R / MWR / I / MA / MS	OB / UD / US	HH-OB / HH-US
Disposable Diapers (ND)	I / MWR / MA / MS	UD / US / OB	HH-OB / HH-US
Other (ash, dirt, dust, soil, electronic waste) (OT)	MA / MS	UD / US	HH-US

The matrix was developed by combining three considerations. First, waste-management suitability from the literature was used to identify the treatment and disposal options that are technically appropriate for each waste fraction based on its physical and compositional characteristics [45]. Under this logic, recyclable materials were prioritized for recovery-oriented pathways, while biodegradable fractions were preferentially assigned to biological treatment options such as CO and BO [45]. Second, these suitability rules were adapted to the Thai context using historical observations from the PCD, so that the matrix reflects not only theoretical best-fit

pathways but also the management conditions actually observed in Thailand, including controlled treatment, uncontrolled disposal, and household-level handling practices. Third, pathway definitions were aligned with IPCC-consistent waste categories to ensure compatibility with the GHG accounting framework; however, IPCC guidance was used to define emission pathways and calculation categories rather than to determine the management priority itself, which follows national management practices.

Thus, the allocation matrix can be interpreted as a rule-based routing framework rather than an arbitrary assignment. It basically identifies which pathways are technically appropriate for each waste component under Thai conditions, while the scenario-specific allocation shares determine the quantity of waste routed to each pathway over time. This structure is designed to reflect both technical suitability and observed management practices, thereby providing a transparent basis for subsequent pathway-specific emission calculations.

For example, PT were first assigned to recycling under controlled management where collection and sorting systems were available. Residual collected PT that were not recovered were then directed to material recovery or incineration-type pathways, depending on their suitability within the controlled system. In contrast, PT outside the formal collection system were represented under unmanaged or household-level practices, including open burning, where such behavior has been observed in the Thai context [46]. Similarly, FW was primarily allocated to biological treatment pathways, particularly CO and BO, under controlled management conditions. However, where such systems were unavailable or where waste was not effectively collected, FW could still enter unmanaged landfill-related pathways or household-level disposal routes, consistent with historical observations. These examples illustrate that the allocation matrix was constructed to reflect both the technical suitability of each pathway and the practical realities of Thailand's waste-management system.

Based on this routing framework, pathway-specific flows were determined by the waste allocation module, in which scenario-specific allocation shares route generated MSW into controlled management, uncontrolled disposal, and household-level practices according to the allocation matrix and scenario-specific assumptions. As a result, the quantity of waste entering each emission sub-module varies over time as a function of both waste generation and pathway allocation.

Following the allocation of waste flows to each pathway, including landfill-related pathways, a common first-order decay-based equation structure was applied, with differences arising from pathway-specific Methane Correction Factors (MCFs) and waste composition. Emissions from incineration and open burning were calculated using pathway-specific emission factors for CH₄ and N₂O, which depend on combustion technology and operating conditions. Similarly, CO and biogas treatment/BO shared a common calculation framework, with variations in CH₄ and N₂O emissions

reflecting process-specific factors such as waste characteristics, the use of bulking materials, temperature, moisture content, and aeration conditions. The equation structures and causal relationships underlying these calculations are depicted in Figures 3-5.

E. Model Validation

Model validation was conducted to assess the ability of the SD model to reproduce historical MSW generation, reflect IPCC-consistent emission dynamics, and plausibly respond to exogenous shocks. MSW generation was evaluated using an out-of-time validation approach, with regression coefficients estimated from 2008-2021 data and model performance tested against unseen observations from 2022-2024 using Mean Absolute Percentage Error (MAPE) and Root Mean Square Error (RMSE).

Emission modules were examined for structural consistency with IPCC FOD assumptions, ensuring that landfill emissions reflect cumulative waste deposition from previous years and that the available historical data capture the dominant contribution of past waste to current emissions.

System behavior during the COVID-19 period was qualitatively evaluated by examining whether the simulated MSW generation reproduced the observed temporary decline and gradual recovery associated with tourism-related demand shocks, without explicit shock calibration.

Total GHG emissions were derived by aggregating pathway-specific estimates calculated using IPCC-consistent methodologies. Accordingly, model evaluation emphasized whether the integrated model produced plausible pathway-level emission patterns and overall system behavior, rather than seeking exact agreement in aggregated emission totals.

The model outputs were further assessed by comparison with Thailand's official national GHG inventory reported in the Biennial Transparency Report (BTR1) [6]. This comparison focused on the dominant emission pathways in the waste sector, particularly landfill disposal, incineration, and open burning, in order to assess whether the pathway-specific magnitudes and overall emission structure were broadly consistent with national reporting.

F. Sensitivity Analysis

To evaluate the robustness of the SD model, sensitivity analysis was conducted at two levels: (1) socio-economic sensitivity of MSW generation and (2) management-related sensitivity of projected GHG emissions under the NZA pathway. The first level was used to examine the uncertainty in future waste generation arising from external socio-economic factors, while the second level was designed to assess how uncertainty in organic-waste routing may affect the remaining mitigation gap in the most mitigation-intensive scenario. The overall design of the sensitivity analysis is summarized in Table IV.

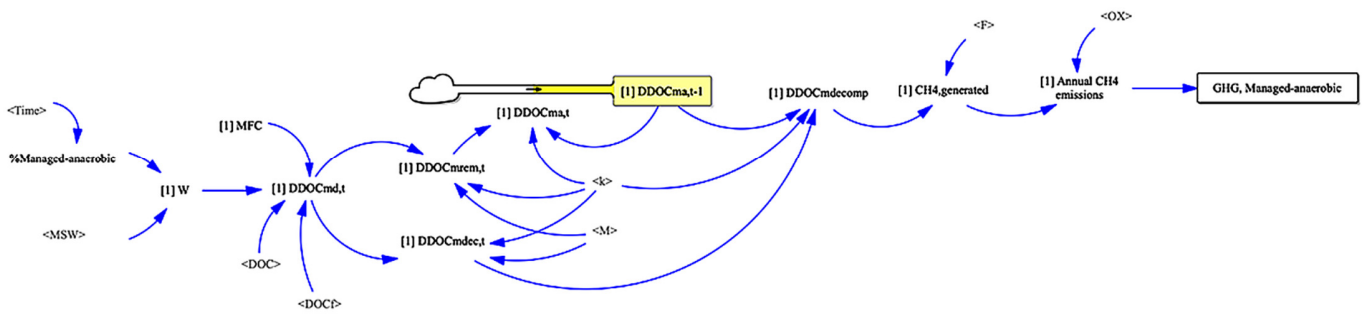


Fig. 3. Stock-flow and causal loop diagram of the equation for calculating GHG emissions from anaerobic landfill waste management methods.

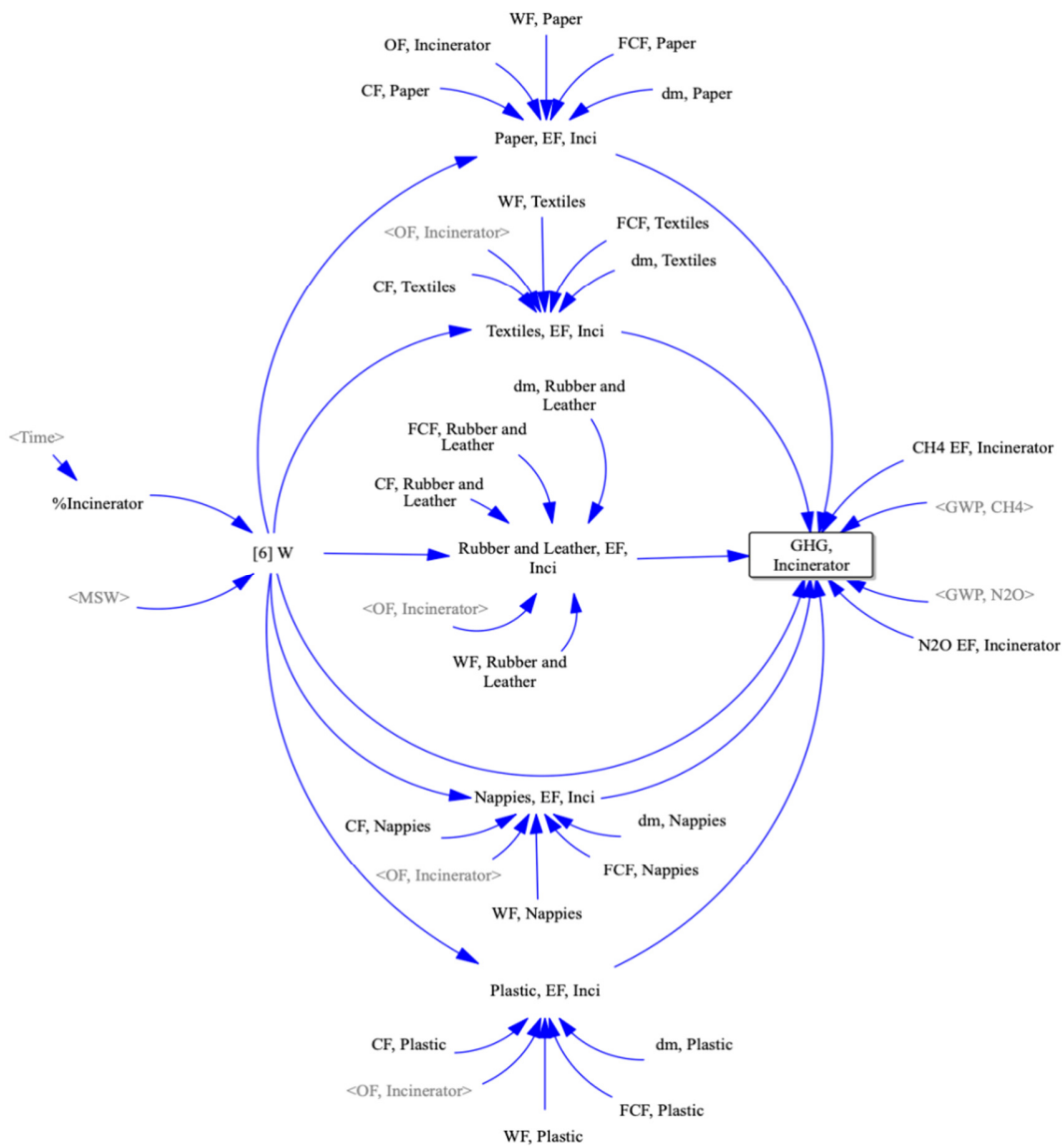


Fig. 4. Causal loop diagram of the equation for calculating GHG emissions from incinerator waste management methods.

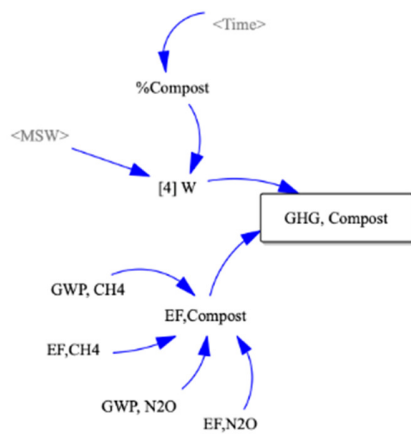


Fig. 5. Causal loop diagram of the equation for calculating GHG emissions from compost waste management methods.

At the socio-economic level, sensitivity analysis was performed by varying two primary exogenous factors, namely

GDP per capita growth rate and tourist arrivals. These variables were selected because they constitute the key inputs to the MSW generation module. Six alternative sensitivity scenarios, together with the base case, were used to establish a plausible range for national MSW generation through 2050. The base case assumed a GDP growth of 2.6% per year, consistent with long-term global projections [47], and tourist arrivals reaching 70 million by 2050 under a moderate recovery trajectory. GDP sensitivity was represented by a high-growth case of 4.0%, aligned with the National Strategy target [48], and a low-growth case of 1.5% [49]. Tourism sensitivity was represented by a high-tourism case of 80 million arrivals, corresponding to approximately two times the historical peak, and a low-tourism case of 45 million arrivals [49]. In addition, two extreme cases were tested: the best case (High GDP/High Tourism) and the worst case (Low GDP/Low Tourism). The response of the MSW generation module to these variations was simulated to identify the most influential leverage points and to evaluate the model's behavioral stability across a range of plausible future conditions.

TABLE IV. SUMMARY OF SENSITIVITY ANALYSIS DESIGN

Sensitivity level	Parameters varied	Cases
Socio-economic sensitivity of MSW generation	GDP per capita growth rate, tourist arrivals	Base case GDP growth at 2.6% per year (consistent with long-term global projections), tourist arrivals reach 70 million by 2050 (assuming moderate recovery)
		High GDP GDP growth at 4.0% per year, aiming towards National Strategy Target
		Low GDP GDP growth at 1.5% per year
		High Tourism Tourist arrivals reach 80 million by 2050, two-fold expansion relative to the historical peak
		Low tourism Tourist arrivals reach 45 million by 2050
		Best case GDP growth at 4.0% per year Tourist arrivals reach 80 million by 2050
		Worst case GDP growth at 1.5% per year Tourist arrivals reach 45 million by 2050
		Baseline NZA reference
Management-related sensitivity of GHG emissions	Total MSW generation bounds, relative variation in Managed Anaerobic (MA) landfill share within the controlled organic waste treatment pathways	Low MSW–Baseline MA Low MSW from socio-economic sensitivity of MSW generation Constant pathway share of baseline NZA
		High MSW–Baseline MA High MSW from socio-economic sensitivity of MSW generation Constant pathway share of baseline NZA
		Low MSW–High MA Low MSW from socio-economic sensitivity of MSW generation +20% pathway share of MA
		Low MSW–Low MA Low MSW from socio-economic sensitivity of MSW generation -20% pathway share of MA
		High MSW–High MA High MSW from socio-economic sensitivity of MSW generation +20% pathway share of MA
		High MSW–Low MA High MSW from socio-economic sensitivity of MSW generation -20% pathway share of MA

Building on these socio-economic sensitivity bounds, the robustness of projected GHG emissions was further examined under the NZA pathway. Two sources of uncertainty were considered: the total MSW generation and the allocation of

organic waste within the controlled organic waste treatment pathways. Uncertainty in waste generation was represented by the minimum and maximum MSW levels derived from the socio-economic sensitivity analysis described above.

Management-related sensitivity was assessed by varying the share of organic waste routed to the MA landfill within the controlled organic waste treatment pathways of the NZA scenario in 2050. These treatment pathways comprised CO, BO, Managed Semi-aerobic (MS) landfill, and MA landfill, which together accounted for 23.64% of the total MSW. The analysis was intentionally limited to controlled organic waste treatment pathways because the NZA scenario is formulated as a mitigation-oriented pathway in which future emission reductions are expected to be driven primarily by improvements in formal waste collection, source separation, and treatment system performance.

Under this framework, uncertainty in the allocation of organic waste among technically managed pathways is more policy-relevant than uncertainty in uncontrolled disposal routes, which are assumed to be progressively minimized under the NZA trajectory. In addition, uncontrolled waste disposal represents system leakage and informal handling practices that are less directly governed by the operational efficiency of formal diversion measures.

The baseline MA share within these controlled organic waste treatment pathways was varied by $\pm 20\%$ on a relative basis, and the corresponding mass was reallocated to CO and BO in proportion to their baseline shares. This approach was adopted to represent uncertainty in the effectiveness of source separation and biological treatment implementation under the NZA pathway. Accordingly, seven sensitivity cases were simulated: the baseline NZA reference case, Low MSW-Baseline MA, High MSW-Baseline MA, Low MSW-High MA, Low MSW-Low MA, High MSW-High MA, and High MSW-Low MA. Together, these cases were utilized to evaluate how uncertainty in waste generation and organic-waste routing may influence the remaining mitigation gap under the most mitigation-intensive pathway.

G. Scenario Development

Thailand has established several national policy frameworks to improve MSW management while reducing environmental impacts associated with waste disposal. Two key policy instruments guiding waste management development are the National Solid Waste Management Master Plan (2016-2021) and the National Action Plan on Waste Management (Phase II, 2022-2027) [50]. These national strategies aim to strengthen waste collection systems, expand environmentally sound treatment and disposal infrastructure, promote recycling and resource recovery, and reduce environmentally harmful practices such as open dumping and open burning. In parallel, Thailand's climate policy framework has increasingly emphasized GHG mitigation across major sectors, including waste management. The updated NDC 3.0 sets a national target of reducing these emissions by 47% by 2035 relative to the 2019 baseline [2].

To explore how these policy directions may influence long-term waste-sector emissions, four cases were developed within the SD model to represent alternative policy trajectories. These scenarios range from the continuation of existing practices to progressively more ambitious pathways aligned with national

waste management policies, circular economy transitions, and national climate mitigation targets.

Four scenarios were developed to explore MSW management pathways and associated GHG emissions in Thailand over the period 2025-2050 (Table V). These cases represent different policy and system transformation trajectories, ranging from the continuation of current practices to ambitious mitigation-oriented strategies.

TABLE V. SCENARIO ASSUMPTIONS FOR MSW MANAGEMENT PATHWAYS BASED ON THE 2021 BASELINE (2025–2050).

Scenarios/parameter	Waste treatment and disposal structure	Recycling and material recovery rate	Share of biodegradable (food) waste in MSW
BD	68.73% (baseline, 2021)	Maintained at baseline shares	Maintained at the most recent (2024) composition
NR	Controlled management increased to 80%, with landfilling implicitly reduced through FW reduction measures	Increased packaging waste recycling, with recycling rates of PT (100%), GL (86%), paper (47%), and aluminum (81%)	FW share reduced (28%)
CR	Landfilling strongly reduced, with organic FW increasingly diverted to CO and biogas treatment, and residual disposal limited to <10% of total MSW	Substantially expanded recycling and recovery, consistent with international circular economy benchmarks	Maintained at the most recent (2024) composition
NZA	Controlled management maximized and landfilling minimized, prioritizing diversion pathways with the lowest GHG emission intensity	Optimized recycling and recovery, emphasizing materials and pathways with the highest GHG mitigation potential	Maintained at reduced levels defined under NR

The BD scenario assumes the continuation of the waste management structure and operational practices observed in the 2021 baseline year, with no additional policy interventions or accelerated targets beyond those already achieved. This situation serves as the reference case against which the impacts of alternative policy and system transformation scenarios are evaluated. Within the uncollected MSW fraction, household open burning represents the dominant disposal practice [46]. In particular, 2021 was when controlled dumping was formally classified as an inappropriate disposal practice. Meanwhile, the objectives of the National Action Plan on Waste Management [50] were largely achieved by 2019 [51]. Under the BD scenario, the treatment and disposal method rates documented for 2021 are assumed to persist over time across both the formal waste management system and household-level practices, with no additional policy interventions or accelerated targets beyond those already achieved by the baseline year.

Measures introduced under National Action Plan Phase II [51] are therefore examined separately under the NR scenarios.

The NR reflects the implementation of Thailand's National Action Plan on Waste Management (Phase II, 2022–2027) [51] and represents a policy-continuity pathway based on officially adopted national strategies. The NR scenario is structured around three key policy directions: (i) the expansion of environmentally sound and appropriate waste treatment and disposal, (ii) enhanced utilization of packaging waste through recycling and material recovery, and (iii) reduced FW generation. Together, these measures are assumed to shape the future waste management structure under NR, with scenario implementation achieved through adjustments to waste pathway allocation parameters while maintaining the same socioeconomic drivers as in the BD case.

The CR scenario is based on international best practices in waste management, with particular reference to the European Union Waste Framework Directive and related policy briefs. It assumes a substantial expansion of material recovery and recycling systems, targeting 65% recycling and recovery and less than 10% landfilling by 2035. The CR scenario represents a transformative shift toward circular economy principles, emphasizing waste prevention, material efficiency, and landfill diversion [52].

In contrast, the NZA scenario is formulated in recognition that Thailand already has an established waste management policy framework under the NR scenario, while its updated NDC 3.0 sets a target of reducing national GHG emissions by 47% by 2035 relative to the base year of 2019. Accordingly, the NZA scenario builds upon the NR pathway and further intensifies waste management measures by prioritizing pathways with the highest GHG mitigation potential, including additional landfill diversion and improved treatment efficiency.

The CR and NZA scenarios were therefore designed to reflect circular economy transitions within the structure of the SD model. In this framework, circularity is represented through the diversion of waste flows away from disposal pathways and toward recovery-oriented processes. Recyclable materials are retained within technical cycles through expanded recycling and material recovery systems, while biodegradable waste is redirected to biological recovery pathways such as CO and biogas treatment. These structural changes reduce the volume of waste entering landfill disposal, which is the dominant source of methane emissions in the waste sector. Consequently, the mitigation effects observed in the CR and NZA scenarios arise not only from improved recycling performance but also from a systemic shift toward circular waste flows with lower GHG emission intensity.

Policy scenarios are operationalized by modifying key allocation parameters, including recycling and material recovery rates, shares of controlled waste management, and disposal pathway distributions. In this way, the BD, NR, CR, and NZA scenarios represent alternative policy trajectories that

influence how generated waste is routed across recycling, CO, anaerobic treatment, incineration, and landfill pathways over time.

III. RESULTS

A. Model Validation

1) Statistical Validation of MSW Generation

Multiple linear regression analysis indicated that the selected socio-economic factors accounted for approximately 88.4% of the variance in historical waste generation (adjusted $R^2 = 0.925$). The detailed statistical parameters, presented in Table VI, confirmed that both GDP per capita and tourist arrivals are significant predictors at the 95% confidence level ($p < 0.05$). The coefficients for both variables were positive, quantifying the direct structural impact of economic growth and tourism intensity on national waste volumes. This finding aligns with observations in other developing contexts, such as Algeria, where waste generation was found to correlate positively with the standard of living and exhibited significant seasonal variations due to consumption habits [53]. Regarding predictive capability, the out-of-time validation against the testing dataset (2022-2024) yielded an MAPE of 1.31% and an RMSE of 0.45 Mt per year. These metrics demonstrated that the model effectively tracks the observed post-pandemic trajectory. Consequently, the simulation framework was deemed sufficiently accurate for projecting future MSW generation trends.

TABLE VI. STATISTICAL PARAMETERS OF THE MULTIPLE LINEAR REGRESSION MODEL FOR MSW GENERATION.

Predictor variable	Intercept (constant)	GDP per capita	Tourist arrivals
Coefficient (β)	-5.5232E+07	8.0784E+06	7.9596E-02
Std. error	1.2428E+07	1.2753E+06	1.0832E-02
t-statistic	-4.4441E+00	6.3346E+00	7.3479E+00
p-value	9.8835E-04	5.5627E-05	1.4521E-05

2) Structural Validation of Landfill Emission Dynamics

The sufficiency of the available historical dataset (2008-2024) relative to the IPCC-recommended 50-year horizon was evaluated by simulating cumulative residual GHG emissions under a constant waste input scenario. Figure 6 demonstrates that the simulated emission trajectory converges with the long-term theoretical model (starting in 1971). Quantitative analysis indicated that by 2025, the model accounts for 98.26% of the total theoretical emissions. This proportion will increase to 99.95% by 2040 and will reach 100.00% by 2050. This convergence rate is associated with the high decay constants (k) characteristic of Thailand's tropical climate and organic-rich waste composition, which result in faster methane generation. Consequently, the contribution of waste deposited prior to 2008 becomes minimal within this timeframe, suggesting that the current dataset is adequate for projected long-term emissions.

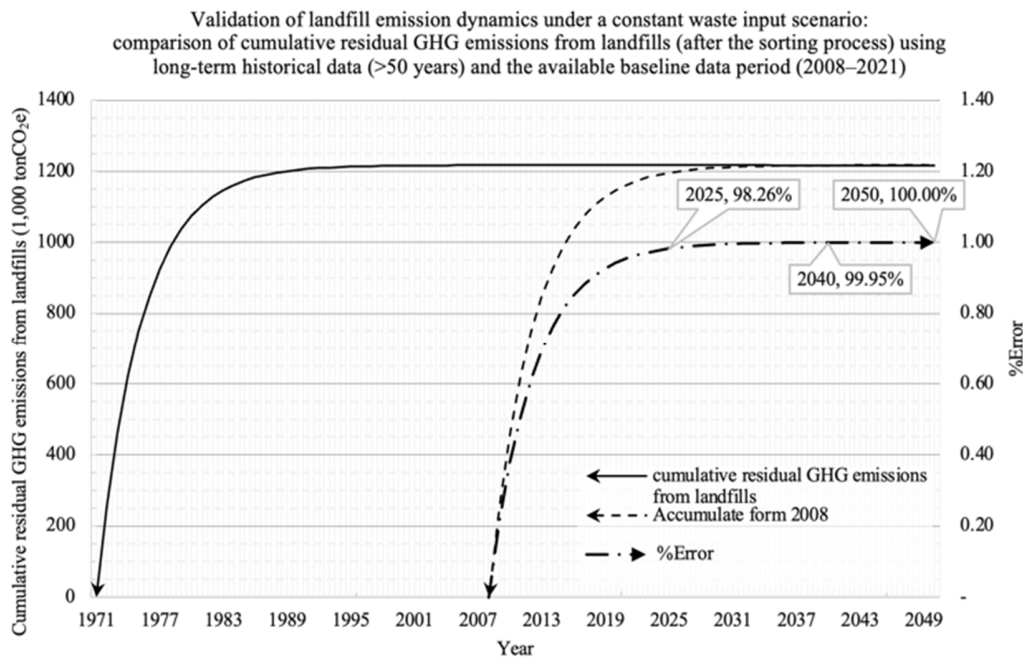


Fig. 6. Validation of landfill emission dynamics under a constant waste input scenario: Comparison of cumulative residual GHG emissions from landfill (after the sorting process) using long-term historical data (>50 years) and the available baseline data period (2008–2021).

3) System Behavior under COVID-19 Disruption

The system’s response to external disruptions is presented in the time-series comparison (Figure 7). The simulation reflects the structural deviation associated with the COVID-19 pandemic, specifically the contraction in waste generation during 2020–2021, which corresponds to the reduction in tourism activity.

shocks without requiring artificial dummy variables. Although the aggregate structure limits the representation of minor short-term fluctuations, the timing and direction of the simulated response are consistent with observed trends, supporting the model’s suitability for scenario-based analysis.

4) Pathway-Level Consistency with the National GHG Inventory (BTR1)

The model results were compared with Thailand’s official GHG inventory reported in the BTR1 in order to examine the consistency of emission patterns across major waste-management pathways [6]. As presented in Table VII, emissions from disposal sites were the dominant source in both datasets throughout 2021–2022. In particular, managed disposal sites accounted for the largest share of waste-sector emissions in both BTR1 and the model results, increasing from 56.7% to 61.6% in BTR1 and remaining relatively stable at 58.3–59.8% in the model results. Unmanaged disposal sites represented the second-largest pathway in both datasets, contributing 34.7–38.7% in BTR1 and 37.9–38.9% in the model results. By contrast, CO and waste incineration accounted only for marginal shares in both cases, indicating that the overall pathway structure of emissions was broadly consistent between the national inventory and the model estimates. In addition, open burning was reported only in the model results, where it declines from 4.1 Mt CO₂e in 2021 to 3.7 Mt CO₂e in 2022, reflecting the explicit inclusion of household-level unmanaged burning practices that are not directly reported as a comparable disaggregated category in BTR1. Overall, while exact agreement in absolute emission totals is not expected, the comparison indicated that the model reproduces the dominant emission pathways and their relative contribution structure in a manner broadly consistent with national reporting.

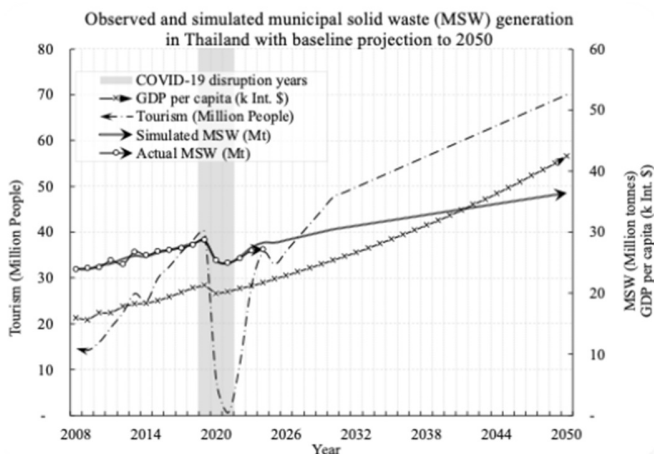


Fig. 7. Comparison of observed and simulated MSW generation in Thailand during the validation period (2008–2024), highlighting the COVID-19 disruption years, with the baseline projection extended to 2050.

As shown in Figure 7, the simulated trajectory follows the observed data trend, exhibiting a comparable short-term deviation and a subsequent gradual recovery driven by the resurgence of tourist arrivals. This alignment indicates that the model accounts for the first-order effects of tourism demand

TABLE VII. COMPARISON OF PATHWAY-SPECIFIC GHG EMISSIONS BETWEEN THAILAND'S NATIONAL INVENTORY (BTR1) AND MODEL ESTIMATES, 2020–2022.

Waste management pathway	Pathway-specific GHG emissions (Mt CO ₂ e) and pathway share (%)							
	Y2021				Y2022			
	BTR1		Model results		BTR1		Model results	
Managed disposal sites (MA+MS)	5.6	56.7%	7.4	59.5%	6.4	61.6%	7.0	58.3%
Unmanaged disposal sites (US+UD+HH-US)	3.8	38.7%	4.7	37.9%	3.6	34.7%	4.7	38.9%
CO	0.1	1.4%	0.2	1.5%	0.1	1.1%	0.2	1.6%
Waste incineration (I)	0.2	<0.1%	0.1	<0.1%	0.2	<0.1%	0.1	<0.1%
Open burning (OB+HH-OB)	NA		4.1	NA	NA		3.7	NA

Note: Pathway share (%) represents the contribution of each pathway to total waste-sector GHG emissions in the corresponding dataset and year. Open burning is reported only for the model results because directly comparable disaggregated values are not explicitly available in BTR1.

B. Future MSW Generation and Sensitivity to Socio-Economic Drivers

Under the BD scenario, national MSW generation is projected to reach approximately 36.4 Mt by 2050 (Figure 7). This trajectory assumes a steady economic recovery (GDP growth of 2.6% p.a.) and a resurgence of tourism to 70 million arrivals, reflecting the post-pandemic normalization of consumption patterns. The sensitivity analysis across the six socio-economic cases indicated that MSW generation is responsive to both long-term economic shifts and tourism demand shocks. By 2050, the projected MSW volumes will exhibit the following variations (Figure 8):

- **Economic Impact:** Under the High GDP scenario (4.0% growth), MSW volumes will increase to 39.3 Mt, while the Low GDP scenario (1.5% growth) will result in a reduction to 34.1 Mt.
- **Tourism Impact:** Variations in international arrivals will lead to projections of 37.2 Mt under the High Tourism case and 34.4 Mt under the Low Tourism case.
- **Extreme Ranges:** The Best Case scenario will establish the upper bound at 40.1 Mt, as well as 32.2 Mt at the Worst Case.

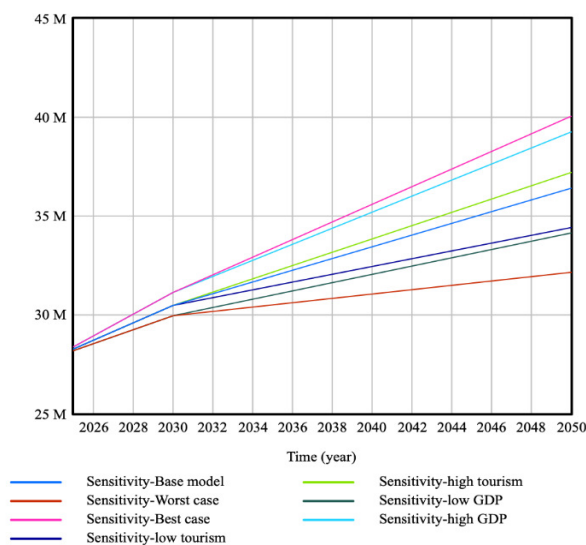


Fig. 8. Sensitivity analysis of projected MSW generation (2024–2050) under varying socio-economic and tourism recovery scenarios.

The deviation of approximately 7.9 Mt between the extreme scenarios reflected the elasticity of waste generation relative to socio-economic conditions. These results indicate that while economic growth is a primary driver, tourism serves as a multiplier, leading to an uncertainty range of approximately 21.7% relative to the 2050 baseline. These findings support the necessity for flexible waste management capacity planning to accommodate various plausible future trajectories.

C. Waste Allocation Shifts and GHG Emission Pathways

1) Shifts in Waste Management Flows

The implementation of alternative policy scenarios drives significant shifts in waste allocation over the study period. In the BD (Figure 9(a)), waste management reflects a continuation of current practices. As of 2021, only 13.3 Mt of MSW entered controlled systems, while substantial fractions flowed to uncontrolled disposal (4.89 Mt) and household-level management (2.9 Mt). Without intervention, this disposal-oriented structure persists throughout the simulation.

By 2030, the NR scenario (Figure 9(b)) will increase controlled management to 17.2 Mt, driven by a policy-led expansion of pre-sorting. However, deeper structural reorientations emerge under the alternative scenarios. The CR scenario (Figure 9(c)) will reduce landfill dependency to approximately 21.1% by 2030 through expanded recycling (18.2 Mt). Similarly, the NZA case (Figure 9(d)) will prioritize biological treatment for organic fractions, increasing recycling throughput to 19.3 Mt, while minimizing residual disposal flows.

By 2050, the divergence between scenarios becomes the most pronounced. The CR scenario (Figure 9(e)) will expand recycling capacity to 22.3 Mt, stabilizing the landfill share at approximately 10%. In comparison, the NZA scenario (Figure 9(f)) achieves the highest level of resource recovery, raising controlled management to 19.7 Mt and recycling to 27.3 Mt. Under this climate-optimized pathway, the system achieves minimal reliance on disposal, effectively diverting most biodegradable waste to biological treatment facilities to maximize emission abatement. Overall, the results indicate that policy assumptions mainly affect waste allocation across management pathways, as defined by the suitability-based allocation matrix, while total waste quantities remain unchanged. These differences are examined further in the comparative GHG emission scenario analysis.

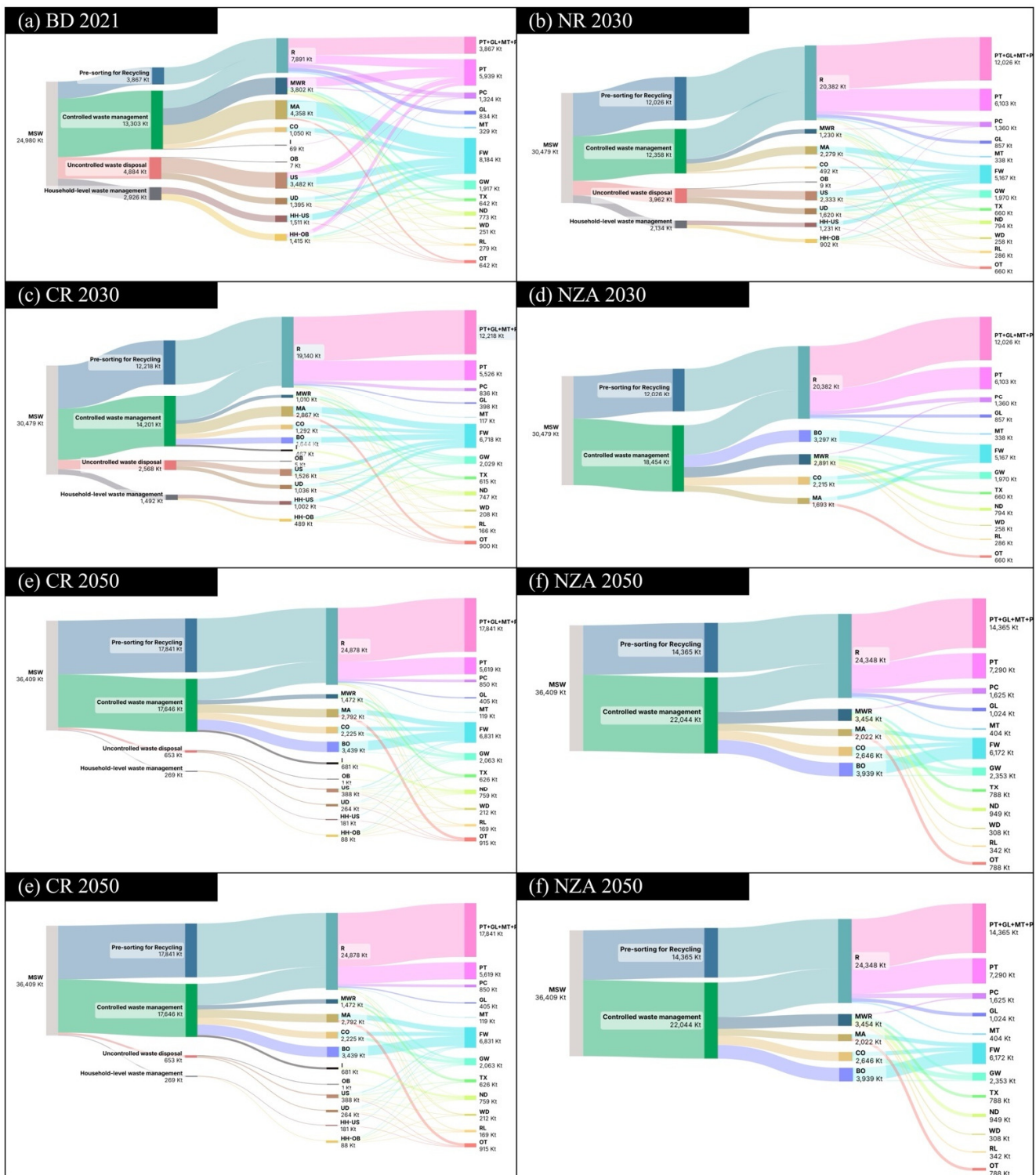


Fig. 9. Material flow of MSW across management pathways.

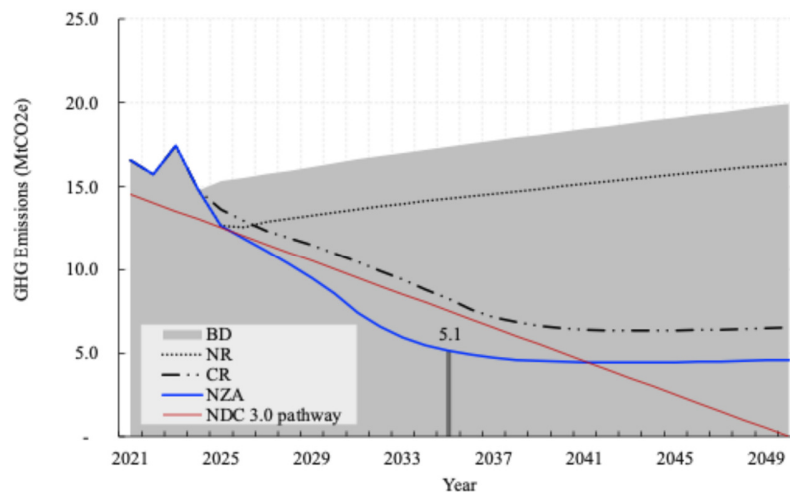


Fig. 10. Projected GHG emissions under BD, NR, CR, and NZA (2024-2050).

2) Comparative GHG Emission Trajectories

The projected GHG emission trajectories exhibited significant divergence depending on the structural interventions applied. Under the BD scenario, net emissions rose steadily from 16.6 Mt CO₂e in 2021 to 19.9 Mt CO₂e by 2050 (Figure 10). This trend reflected the continued dominance of anaerobic landfilling as the primary disposal method. The NR scenario moderated this growth to 16.4 Mt CO₂e, indicating that incremental expansions in recycling capacity alone are insufficient to reverse the upward emission trend. In contrast, the high-ambition cases demonstrated the potential for deep decarbonization. The CR scenario achieved a substantial decline, with emissions falling to approximately 6.5 Mt CO₂e by 2050. This reduction is driven by aggressive material recovery targets (70% recycling) and a strict limit on landfilling (<10% by 2035).

However, the NZA case delivered the most profound mitigation, reaching a low of 4.6 Mt CO₂e by 2050. This superior performance is attributable to the strategic prioritization of biological treatment over general recycling. By diverting organic waste toward CO and anaerobic digestion, the NZA strategy effectively eliminates methanogenic potential at the source, proving more effective than the volume-reduction approach of CR.

3) Cumulative Emission Analysis

The long-term implications of these strategies were further quantified by the cumulative carbon footprint over the 2025-2050 period (Figure 11). While the disposal-heavy structure of the BD scenario resulted in a total burden of 525.9 Mt CO₂e, the structural optimization in the NZA scenario limited the cumulative load to 227.2 Mt CO₂e. This represents a 57% reduction relative to the baseline (2025), confirming that a significant shift from landfill dependence to targeted organic waste recovery is essential for limiting atmospheric GHG accumulation.

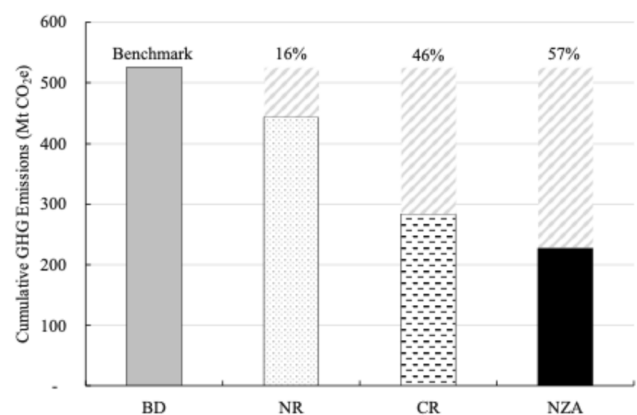


Fig. 11. Cumulative GHG emissions from the MSW sector (2021-2050) and percentage reductions relative to the BD scenario.

D. Disaggregated Emission Sources and Key Leverage Points

The disaggregation of emissions under the BD scenario underscored the dominant role of landfill-related pathways in shaping the overall emission profile (Figure 12(a)). By 2050, the MA landfill will constitute the largest share of total emissions at 37.3%, followed by the UD landfill at 25.9%. The US landfill will contribute 4.8%, whereas the MS landfill will account for less than 0.1%. Open burning will remain a persistent secondary source, contributing approximately 30% of the total emissions and reflecting the continued importance of household-level disposal practices. Overall, these results indicate that the BD pathway is governed primarily by MA and UD, with open burning providing an additional substantial contribution, while CO, biogas, and incineration remain relatively minor. This pathway structure explains why total emissions remain high under the BD scenario.

The comparative analysis identified organic waste diversion as the primary leverage point for sector-wide mitigation. This stronger mitigation effect was not explained solely by the higher methane potential of biodegradable materials, but also by the structural role of organic waste within Thailand's waste

stream. Because organic fractions constitute approximately half of total MSW, their diversion substantially reduces the mass flow entering the highest-emission pathways, particularly landfilling and unmanaged household disposal. In contrast,

increasing recycling rates for materials such as PT and paper affects smaller fractions of the waste stream and typically reduces landfill inflow to a lesser extent, since sorting residuals and non-recyclable fractions remain within the disposal system.

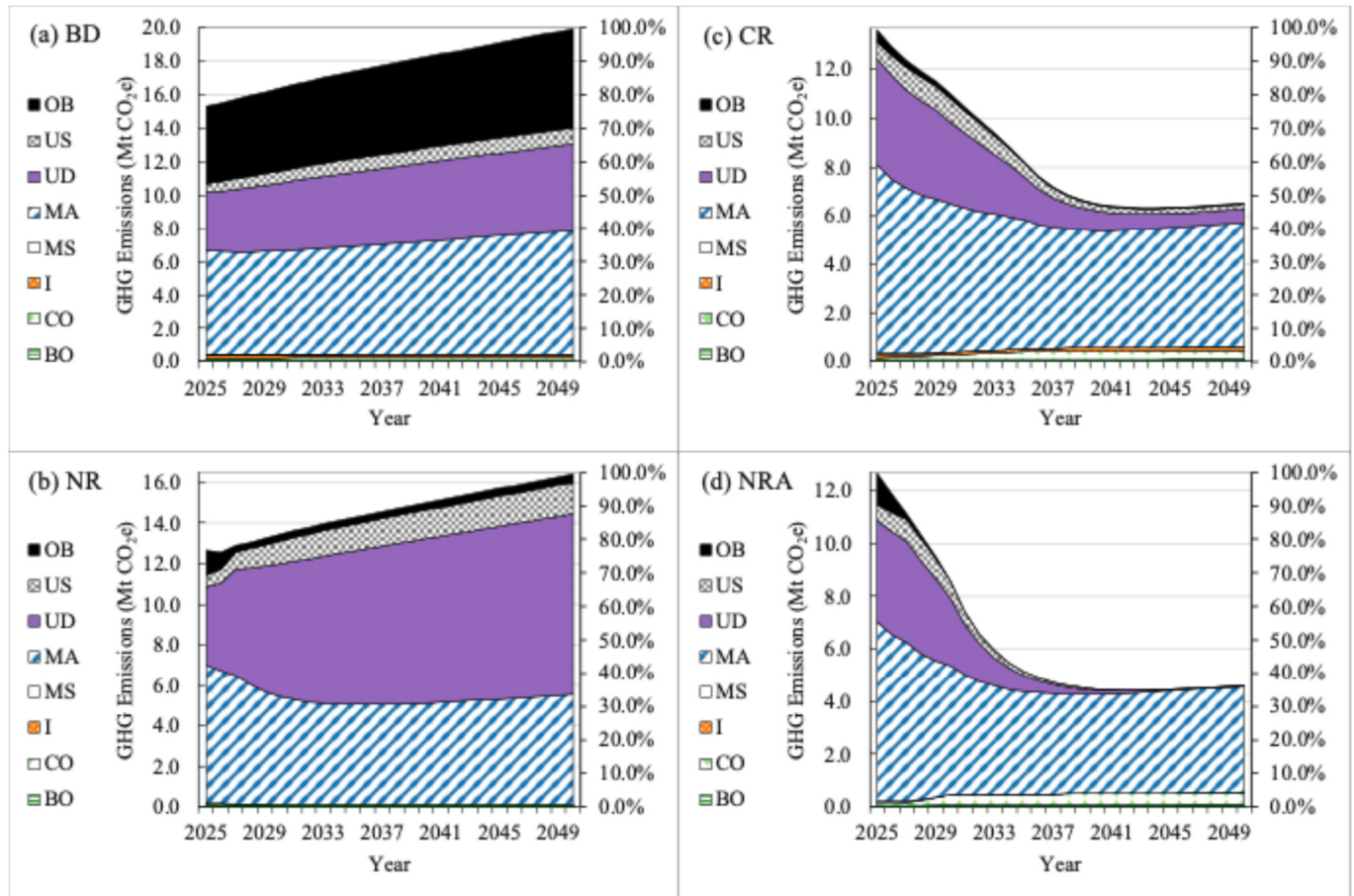


Fig. 12. Disaggregated GHG emissions by waste management pathway under different future scenarios in Thailand (2025-2050).

The divergence between the CR and NZA trajectories illustrated this mechanism; while CR focused on broad material recovery, NZA explicitly prioritized the diversion of biodegradable fractions to CO and Mechanical-Biological Treatment (MBT). This targeted strategy effectively eliminated the methane generation potential at the source, explaining why NZA achieves deeper reductions than CR despite similar recycling rates. This finding confirms that for tropical contexts such as Thailand, climate-optimized waste allocation by prioritizing biological treatment over general disposal is more effective for GHG abatement than purely volume-based diversion targets.

E. Sensitivity of Projected GHG Emissions under the NZA Pathway

The sensitivity analysis indicated that the projected GHG emissions under the NZA pathway remained strongly dependent on both future waste generation and the allocation of organic waste within the controlled treatment block (Table VIII, Figure 13). Across all seven cases, emissions declined over time, but the magnitude of reduction varied substantially

depending on the assumed combination of MSW generation and MA landfill share. The widest divergence emerged under the combined sensitivity cases, with projected emissions in 2050 ranging from 3.4 MtCO_{2e} under the Low MSW-Low MA case to 5.8 MtCO_{2e} under the High MSW-High MA case, compared with 4.6 MtCO_{2e} in the baseline NZA scenario. This corresponds to a deviation of approximately -25.3% to +27.2% relative to the reference pathway.

The results further revealed that management-related uncertainty exerted a stronger influence on GHG outcomes than uncertainty in total MSW generation alone. In 2050, varying MSW generation while keeping baseline MA shares will result in emissions of 4.1 MtCO_{2e} in the Low MSW-Baseline MA case and 5.0 MtCO_{2e} in the high-MSW case, corresponding to changes of -10.2% and +8.8% relative to the baseline NZA scenario. In contrast, changing the MA share within the controlled organic waste treatment pathways will produce substantially larger deviations. Under low MSW conditions, emissions will increase from 3.4 MtCO_{2e} in the Low MA case to 4.8 MtCO_{2e} in the High MA case, while

under high MSW conditions, they will range from 4.2 to 5.8 MtCO₂e. These findings indicate that the effectiveness of source separation and organic-waste diversion to biological treatment pathways is a crucial determinant of the remaining mitigation gap under the NZA pathway.

TABLE VIII. PROJECTED GHG EMISSIONS UNDER SEVEN SENSITIVITY CASES FOR THE NZA PATHWAY IN 2025, 2035, AND 2050.

Sensitivity cases	Y2025	Y2035	Y2050
Baseline Scenario (NZA reference)	12.7 MtCO ₂ e/yr	5.1 MtCO ₂ e/yr	4.6 MtCO ₂ e/yr
High MSW - Baseline MA	12.7 MtCO ₂ e/yr	5.3 MtCO ₂ e/yr	5.0 MtCO ₂ e/yr
Low MSW - Baseline MA	12.7 MtCO ₂ e/yr	5.0 MtCO ₂ e/yr	4.1 MtCO ₂ e/yr
Low MSW - High MA (+20%)	12.6 MtCO ₂ e/yr	5.7 MtCO ₂ e/yr	4.8 MtCO ₂ e/yr
Low MSW - Low MA (-20%)	12.7 MtCO ₂ e/yr	4.4 MtCO ₂ e/yr	3.4 MtCO ₂ e/yr
High MSW - Low MA (-20%)	12.7 MtCO ₂ e/yr	4.6 MtCO ₂ e/yr	4.2 MtCO ₂ e/yr
High MSW - High MA (+20%)	12.6 MtCO ₂ e/yr	6.0 MtCO ₂ e/yr	5.8 MtCO ₂ e/yr

These outcomes confirm that biodegradable waste diversion from landfill is the most influential mitigation leverage point in the system. Under the NZA pathway, CO and BO together account for approximately 18.1% of the total MSW by 2050, while landfill disposal is reduced to 5.6%. A $\pm 20\%$ variation in the share of organic waste sent to managed anaerobic landfill changes projected 2050 emissions from 3.4 to 5.8 MtCO₂e, corresponding to a deviation of -25.3% to $+27.2\%$ relative to the baseline NZA case. In practice, achieving this level of diversion in Thailand will depend on more consistent household source separation, expanded biological treatment capacity, and stronger municipal collection and transport systems.

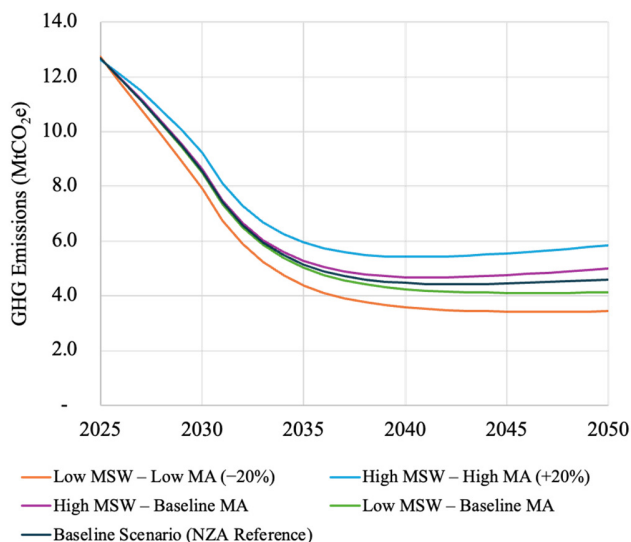


Fig. 13. Projected GHG emissions (MtCO₂e) under alternative MSW generation levels and MA shares in the NZA pathway (2025-2050).

IV. DISCUSSION

A. Comparison with Previous Studies in Thailand

In addition to validating against historical observations, the baseline projection was examined in relation to previous MSW generation estimates for Thailand. Specifically, authors in [37] projected MSW generation of approximately 20-21 Mt by 2030, while authors in [7, 54] reported higher estimates ranging from 30.7 to 34.9 Mt by 2030 and approximately 39.6 Mt by 2050, respectively. The projected trajectory in this study followed a moderate growth path within the range of these existing estimates. This positioning provides contextual consistency with prior literature while integrating updated post-COVID recovery dynamics, ensuring that the baseline serves as a robust reference to evaluate mitigation potentials.

To further assess the possibility of the projected GHG emissions, the results of the present study were compared with previous studies that explicitly quantified waste-sector emissions in Thailand. In particular, the projected emissions under the baseline scenario were compared with a reported estimate of 19.0 MtCO₂e/yr for MSW-related emissions [54]. That research further identified landfills and dumpsites as the dominant emission source, accounting for approximately 95% of the total GHG emissions. In the present study, total waste-sector emissions under the BD scenario are projected to reach approximately 19.9 MtCO₂e/yr by 2050, with landfill and dumpsite methane accounting for roughly 68% of the total emissions.

Although differences in absolute values are observed, these are likely attributable to differences in methodological assumptions, waste composition data, historical baseline periods, and pathway definitions. For example, the present study applied updated national waste statistics, extended the historical baseline to 2008-2024, and explicitly incorporated dynamic pathway allocation within the SD framework. Despite these differences, the dominance of landfill-related methane emissions across studies supports the plausibility of the projected GHG trajectories obtained in this study.

B. Comparison with Studies from Similar Regional Contexts

The projected emissions were also compared with studies conducted in countries with similar waste management characteristics in Southeast Asia, particularly Singapore and Malaysia, to further contextualize the model results.

For instance, a study conducted in Singapore estimated waste-sector emissions of approximately 0.38 MtCO₂e/yr, with controlled incineration identified as the dominant treatment pathway due to the country's highly centralized waste management system. In contrast, landfill emissions represented a smaller share of total waste-sector emissions in Singapore compared with Thailand, reflecting the extensive use of waste-to-energy incineration and strict waste collection coverage [55].

Similarly, studies in Malaysia reported waste-sector emissions of approximately 15.9 MtCO₂e/yr, with landfill emissions accounting for approximately 31% of total waste-sector emissions [56]. These findings are structurally similar to the results of the present study, where landfill disposal remained the dominant emission source due to the high organic

fraction of municipal waste and the continued reliance on landfill-based waste management.

Although direct numerical comparisons are limited by differences in system boundaries, waste composition, and modeling assumptions across studies, the overall emission patterns observed in this study aligned with those reported for other Southeast Asian countries.

C. Implications of Scenario-Based Mitigation Pathways

The comparative analysis highlights a crucial divergence in emission trajectories. If Thailand's MSW sector continues along the BD pathway, emissions are projected to reach 18.0 MtCO₂e by 2050, a trajectory that is fundamentally misaligned with national climate commitments. The NR scenario moderates this growth but fails to reverse the upward trend, indicating that incremental improvements in recycling efficiency alone are insufficient to achieve Thailand's mitigation goals. In contrast, the high-ambition scenarios demonstrate that substantial decarbonization of the waste sector is technically achievable. The NZA scenario, in particular, yields the most rapid and sustained reductions (Figure 10). Under this pathway, emissions declined sharply during the late 2020s and will fall to 5.1 MtCO₂e by 2035, thereby aligning with Thailand's updated NDC 3.0 target of a 47% absolute reduction relative to the 2019 baseline (16.0 MtCO₂e).

However, the NZA scenario should be interpreted as a net-zero alignment pathway rather than a demonstration that the waste sector itself achieves net zero by 2050. Although emissions continue to decline thereafter, reaching approximately 4.2 MtCO₂e by 2050, this value remains positive, indicating that residual emissions persist under the modeled intervention set. Therefore, while NZA substantially reduces sectoral emissions and aligns the waste sector with the national decarbonization trajectory, it does not fully eliminate emissions by mid-century.

Additional measures would be required for the waste sector to approach sectoral net zero. These may include wider deployment of landfill gas capture and utilization, methane oxidation cover systems for disposal sites, deeper diversion of biodegradable waste to CO or anaerobic digestion, stricter control of household-level open burning, and, where residual emissions remain unavoidable, the use of high-integrity offset mechanisms. Even so, the contribution of the waste sector should be interpreted as part of an economy-wide mitigation portfolio. The waste sector alone would not be sufficient to secure Thailand's overall NDC 3.0 achievement if major emitting sectors such as energy and transportation fail to meet their respective reduction targets.

D. Role of Organic Waste Diversion in Achieving Deep Emission Reductions

The cumulative emission analysis (Figure 11) further quantified the magnitude of these structural shifts. While the BD scenario resulted in a total burden of 525.9 Mt CO₂e (2021-2050), the NR scenario achieved only a 16% reduction (443.6 Mt CO₂e). However, the structural interventions in CR and NZA delivered substantial reductions of 46% (283.4 Mt CO₂e) and 57% (227.2 MtCO₂e), respectively. The superior

performance of NZA over CR highlights a crucial policy implication regarding organic waste management. While the CR scenario demonstrates that general recycling benchmarks can significantly reduce landfill dependency, the NZA scenario reveals that explicitly targeting biodegradable waste yields higher mitigation returns. From a circular economy perspective, both the CR and NZA scenarios reduce emissions by redirecting waste away from landfill disposal and toward material and biological recovery pathways. In the CR scenario, this transition is reflected mainly through expanded material recovery and recycling, whereas the NZA scenario extends this logic further by also diverting biodegradable waste to biological treatment pathways such as CO and anaerobic digestion. As a result, the stronger performance of NZA reflects a broader integration of both technical and biological recovery cycles within the waste-management system. By diverting organic fractions - which constitute nearly 50% of Thailand's waste composition [57] - toward CO and anaerobic digestion, the NZA pathway effectively eliminates the methanogenic potential at the source. This finding aligns with previous evidence from Thailand and comparable contexts, identifying methane abatement from landfilled organic waste as the primary leverage point for waste-sector GHG mitigation [4, 54].

The simulation results underscored the significant role of systemic resilience in Thailand's waste management infrastructure, particularly when subjected to tourism-driven volatility. As evidenced by the sensitivity analysis, the fluctuation of international arrivals - ranging from a conservative 45 million to a projected maximum of 80 million visitors by 2050 - presents a significant challenge to the stability of GHG mitigation pathways. While the NR scenario prescribed an ambitious recycling target of approximately 67% by 2030, this study identified a potential implementation gap; if the physical composition of waste or the efficiency of source segregation fails to align with these theoretical recycling mandates, the surplus waste is redirected toward landfill disposal. This phenomenon leads to a non-linear surge in methane emissions, as the landfill's anaerobic environment acts as a long-term carbon sink.

E. System Resilience under Tourism-Driven Waste Variability

The findings of this study are consistent with the resilience gaps observed in other tourism-dependent economies, such as [14], where direct linear correlations between tourist arrivals and waste generation demonstrate how infrastructure often struggles to keep pace with rapid post-pandemic demand recoveries. However, unlike the mature tourism market of Madeira Island [15], which successfully demonstrated a non-linear "decoupling" effect, in which waste per capita declined after reaching a critical tourism volume due to advanced management maturity, Thailand currently lacks such technological leverage. Consequently, Thailand's reliance on centralized targets in the NR scenario necessitates a more robust CR approach to ensure that climate goals remain achievable, even under maximum arrival scenarios (80 million visitors).

F. Study Limitations and Future Research Directions

This study is subject to several limitations. First, the analysis relied on central emission factors and assumed that the waste composition at the point of generation is represented by the composition observed at sorting sites. Second, limitations arose from the use of national-level data, particularly regarding the specific decay characteristics of historical landfill waste stocks.

Third, while technical feasibility is assessed, economic costs were not explicitly modeled. In practice, the implementation of the NZA scenario may face several barriers in the Thai context, including the substantial capital investment required to expand waste diversion infrastructure, the need for sustained household-level source separation and public participation, and the institutional coordination required between national policies and local waste management authorities. Although these socio-economic factors were not explicitly modeled in this study, they represent important considerations for translating the technical mitigation potential identified in the NZA scenario into practical policy actions.

Fourth, the model assumes constant emission parameters based on IPCC default methodological values for waste treatment processes. While these parameters provide a standardized approach for estimating GHG emissions, they do not explicitly capture potential technological improvements over time, such as increased efficiency of anaerobic digestion systems, improvements in CO operations, or enhanced landfill gas capture rates.

Fifth, although predefined policy scenarios were evaluated, future adjustments in implementation effectiveness, extended producer responsibility schemes, and shifts in consumption patterns were not explicitly modeled as dynamic endogenous drivers. Incorporating such evolving policy and behavioral responses would improve the ability of SD models to capture longer-term structural transitions in the waste sector.

Future research could extend this work by integrating SD modeling with techno-economic analysis to evaluate the cost-effectiveness of different mitigation pathways. In addition, incorporating behavioral models of household waste separation and policy instruments such as economic incentives or regulatory interventions could provide deeper insights into the practical feasibility of large-scale organic waste diversion in Thailand.

V. CONCLUSIONS

This study developed a calibrated System Dynamics (SD) model to evaluate decarbonization pathways for Thailand's Municipal Solid Waste (MSW) sector. The findings demonstrated that under the Baseline Dynamic (BD) scenario, waste-related Greenhouse Gas (GHG) emissions are projected to rise to 19.9 Mt CO₂e by 2050, confirming that current practices are incompatible with Thailand's carbon neutrality and Net Zero ambitions. Even the full implementation of current policy targets under the National Roadmap (NR) yields only a modest 16% reduction in cumulative emissions, indicating that incremental efficiency improvements are insufficient to reverse the sector's carbon trajectory.

Substantial mitigation is achievable only through fundamental structural transformations. The analysis identifies the Net Zero Alignment (NZA) scenario as the most effective pathway, which is found to be capable of reducing annual emissions to 4.2 Mt CO₂e by 2050 and achieving a 57% reduction in the cumulative carbon footprint relative to the baseline. This superior performance is driven not merely by higher recycling rates, but by the specific strategic prioritization of diverting organic waste toward biological treatment technologies (Composting (CO) and anaerobic digestion).

Finally, aligning the MSW sector with Thailand's NDC 3.0 requires a decisive policy shift from disposal-oriented management to a circular resource recovery model. Policymakers must prioritize source separation mandates and investment in biological treatment infrastructure to eliminate methane generation at the source. Future efforts should focus on regionalizing these findings and integrating economic cost-benefit analyses to facilitate practical implementation.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no competing interests.

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DATA AVAILABILITY

Data acquisition and calculation are described in the paper and they are available from the corresponding author upon reasonable request.

AI USE AND DECLARATION OF GENERATIVE AI USE

The authors used generative AI tools only for language improvement and proofreading purposes. All scientific content, analysis, and conclusions were developed and verified by the authors.

REFERENCES

- [1] L. Adil, D. Eckstein, V. Künzel, and L. Schäfer, "Climate Risk Index 2026: Who suffers most from extreme weather events?," *Germanwatch e.V.*, Nov. 2025, <https://www.germanwatch.org/sites/default/files/2025-11/CR1%2026%20full%20report.pdf>.
- [2] Department of Climate Change and Environment, "Thailand's Second Nationally Determined Contribution (NDC 3.0)," Ministry of Natural Resources and Environment, Nov. 2025, <https://unfccc.int/sites/default/files/2025-11/TH%20NDC%203.0.pdf>.
- [3] D. Hoornweg, P. Bhada-Tata, and C. Kennedy, "Peak Waste: When Is It Likely to Occur?," *Journal of Industrial Ecology*, vol. 19, no. 1, pp. 117–128, 2015, <https://doi.org/10.1111/jiec.12165>.
- [4] M. Gautam and M. Agrawal, "Greenhouse Gas Emissions from Municipal Solid Waste Management: A Review of Global Scenario," in *Carbon Footprint Case Studies: Municipal Solid Waste Management, Sustainable Road Transport and Carbon Sequestration*, S. S. Muthu, Ed. Singapore: Springer, 2021, pp. 123–160.
- [5] Pollution Control Department, "Thailand State of Municipal Solid Waste Disposal Sites Report 2024," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2024.

- [6] Department of Climate Change and Environment, "Thailand's First Biennial Transparency Report (BTR1)," Ministry of Natural Resources and Environment, Bangkok, Thailand, 2024, <https://unfccc.int/sites/default/files/resource/THAILAND%E2%80%99S%20BTR1.pdf>.
- [7] T. Pudcha, A. Phongphiphat, K. Wangyao, and S. Towprayoon, "Forecasting Municipal Solid Waste Generation in Thailand with Grey Modelling," *Environment and Natural Resources Journal*, vol. 21, no. 1, pp. 35–46, Jan. 2023, <https://doi.org/10.32526/enrj/21/202200104>.
- [8] P. Saengchut, N. Kongritti, and H. Viriya, "Applying of economic index data for municipal solid waste quantity prediction in Thailand," *Asia-Pacific Journal of Science and Technology*, vol. 27, no. 5, Aug. 2022, Art. no. APST-27-05-05, <https://doi.org/10.14456/apst.2022.70>.
- [9] P. Luangpaiboon and L. Ruekksaem, "Developing a Hybrid Regression-Metaheuristic Forecasting Model for University Solid Waste Generation," *International Journal of Environmental Science and Development*, vol. 14, no. 4, pp. 245–251, 2023, <https://doi.org/10.18178/ijesd.2023.14.4.1440>.
- [10] M. Maliyaem, "The Amount of Solid Waste Forecasting using Time Series ANFIS," in *2021 Research, Invention, and Innovation Congress: Innovation Electricals and Electronics (RI2C)*, Bangkok, Thailand, Sept. 2021, pp. 5–8, <https://doi.org/10.1109/RI2C51727.2021.9559807>.
- [11] P. Sukholthaman and A. Sharp, "A system dynamics model to evaluate effects of source separation of municipal solid waste management: A case of Bangkok, Thailand," *Waste Management*, vol. 52, pp. 50–61, June 2016, <https://doi.org/10.1016/j.wasman.2016.03.026>.
- [12] C. Manasakunkit and T. Chinda, "Development of a municipal solid waste dynamic model in Bangkok, Thailand.," *Songklanakarin Journal of Science & Technology*, vol. 39, no. 5, pp. 685–695, Oct. 2017.
- [13] H. Breukelman, H. Krikke, and A. Löhr, "Root causes of underperforming urban waste services in developing countries: Designing a diagnostic tool, based on literature review and qualitative system dynamics," *Waste Management & Research*, vol. 40, no. 9, pp. 1337–1355, Sept. 2022, <https://doi.org/10.1177/0734242X221074189>.
- [14] I. Iuras, P. Raiter, Y. Korobeinykova, and L. Poberezhna, "Methodology of actors analysis and modeling of the amounts of solid municipal waste generation within tourist destinations," *Ecological Questions*, vol. 31, no. 2, pp. 63–69, Apr. 2020, <https://doi.org/10.12775/EQ.2020.014>.
- [15] A. M. Martins and S. Cró, "The Impact of Tourism on Solid Waste Generation and Management Cost in Madeira Island for the Period 1996–2018," *Sustainability*, vol. 13, no. 9, May 2021, Art. no. 5238, <https://doi.org/10.3390/su13095238>.
- [16] "Tourism Statistics 2023," Ministry of Tourism and Sports. 2023. <https://www.mots.go.th/news/category/704>.
- [17] "TAT's 2026 campaign sets sights on 36.7 million tourists." Sawasdee Thailand. 2026. <https://thailand.go.th/issue-focus-detail/tats-2026-campaign-sets-sights-on-367-million-tourists>.
- [18] A. C. H. Pinha and J. K. Sagawa, "A system dynamics modelling approach for municipal solid waste management and financial analysis," *Journal of Cleaner Production*, vol. 269, Oct. 2020, Art. no. 122350, <https://doi.org/10.1016/j.jclepro.2020.122350>.
- [19] Z. Liu, Q. Zhang, and H. Liu, "Prediction of municipal solid waste treatment and disposal in high cold and high altitude area based on system dynamics: a case study of Lhasa," *Environmental Research Communications*, vol. 5, no. 12, Dec. 2023, Art. no. 125006, <https://doi.org/10.1088/2515-7620/ad1164>.
- [20] T. Sakcharoen, W. Niyomaneerat, B. Faiyue, and T. Silalertruksa, "Low-carbon municipal solid waste management using bio-based solutions and community participation: The case study of cultural tourism destination in Nan, Thailand," *Heliyon*, vol. 9, no. 11, Nov. 2023, Art. no. e22025, <https://doi.org/10.1016/j.heliyon.2023.e22025>.
- [21] "Thailand Tourism Industry Outlook 2025-2030," *Intellify*, Mar. 2025, <https://www.intellifyglobal.com/thailand-tourism-industry-outlook-2025/>.
- [22] *Vensim*. (10.4.0), Ventana Systems, Inc. https://vensim.com/download/#Current_Version_1040_released_October_2025.
- [23] *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2006, <https://www.ipcc-nggip.iges.or.jp/public/2006gl/>.
- [24] Pollution Control Department, "Thailand State of Municipal Solid Waste Report 2013," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2013.
- [25] Pollution Control Department, "Thailand State of Municipal Solid Waste Report 2014," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2014.
- [26] Pollution Control Department, "Thailand State of Municipal Solid Waste Report 2015," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2015.
- [27] Pollution Control Department, "Thailand State of Municipal Solid Waste Report 2016," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2016.
- [28] Pollution Control Department, "Thailand State of Municipal Solid Waste Disposal Sites Report 2018," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2018.
- [29] Pollution Control Department, "Thailand State of Municipal Solid Waste Disposal Sites Report 2019," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2019.
- [30] Pollution Control Department, "Thailand State of Municipal Solid Waste Disposal Sites Report 2020," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2020.
- [31] Pollution Control Department, "Thailand State of Municipal Solid Waste Disposal Sites Report 2021," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2021.
- [32] Pollution Control Department, "Thailand State of Municipal Solid Waste Disposal Sites Report 2022," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2022.
- [33] Pollution Control Department, "Thailand State of Municipal Solid Waste Disposal Sites Report 2023," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2023.
- [34] J. A. Araiza-Aguilar, M. N. Rojas-Valencia, and R. A. Aguilar-Vera, "Forecast generation model of municipal solid waste using multiple linear regression," *Global Journal of Environmental Science and Management*, vol. 6, no. 1, pp. 1–14, 2020.
- [35] O. J. Alhanaqat, "Forecasting of the waste generation in Jordan: Alternative econometric approaches," *International Journal of Economics and Finance*, vol. 16, no. 2, pp. 35–50, 2024.
- [36] G. Yu, Z. Li, and R. Dong, "Comparative Prediction of Methane Production In Vitro Using Multiple Regression Model and Backpropagation Neural Network Based on Cornell Net Carbohydrate and Protein System," *Veterinary Sciences*, vol. 12, no. 11, Nov. 2025, Art. no. 1099, <https://doi.org/10.3390/vetsci12111099>.
- [37] R. Intharathirat, P. Abdul Salam, S. Kumar, and A. Untong, "Forecasting of municipal solid waste quantity in a developing country using multivariate grey models," *Waste Management*, vol. 39, pp. 3–14, May 2015, <https://doi.org/10.1016/j.wasman.2015.01.026>.
- [38] A. Maalouf and A. Mavropoulos, "Re-assessing global municipal solid waste generation," *Waste Management & Research*, vol. 41, no. 4, pp. 936–947, Apr. 2023, <https://doi.org/10.1177/0734242X221074116>.
- [39] E. A. Cavalheiro, R. H. Machado, A. S. Castro, and L. R. Falck, "Urban solid waste generation and GDP per capita: a global analysis through the lens of the environmental Kuznets curve," *Contribuciones a las ciencias sociales*, vol. 17, no. 3, pp. e5574–e5574, Mar. 2024, <https://doi.org/10.55905/revconv.17n3-012>.
- [40] "Urban population (% of total population)." World Bank Group, <https://databank.worldbank.org/reports.aspx?source=2&series=SP.URB.TOTL.IN.ZS&country=>.
- [41] "Civil registration population statistics." Statistics on civil registration services. <https://stat.bora.dopa.go.th/stat/statnew/statMenu/newStat/stat/>.
- [42] "World Development Indicators: GDP (current US\$)." World Bank Group, <https://databank.worldbank.org/reports.aspx?source=2&series=NY.GDP.MKTP.CD&country=>.

- [43] 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Intergovernmental panel on climate change, Switzerland, 2019, https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/0_Overview/19R_V0_00_Cover_Foreword_Preface_Dedication.pdf.
- [44] J. Nithikul, Obuli. P. Karthikeyan, and C. Visvanathan, "Reject management from a Mechanical Biological Treatment plant in Bangkok, Thailand," *Resources, Conservation and Recycling*, vol. 55, no. 4, pp. 417–422, Feb. 2011, <https://doi.org/10.1016/j.resconrec.2010.11.004>.
- [45] C. Baskar, S. Ramakrishna, S. Baskar, R. Sharma, A. Chinnappan, and R. Sehrawat, *Handbook of solid waste management: sustainability through circular economy*. Springer, Singapore, 2022.
- [46] Ministry of Digital Economy and Society, *Statistical Yearbook Thailand 2024*. Bangkok, Thailand: National Statistical Office, 2024.
- [47] *The Long View: How will the global economic order change by 2050?*, PwC, 2017, <https://www.pwc.com/gx/en/world-2050/assets/pwc-the-world-in-2050-full-report-feb-2017.pdf>.
- [48] National Strategy Secretariat Office, *National Strategy 2018–2037*, Office of the National Economic and Social Development Council (NESDC), Bangkok, Thailand, 2018, <https://faolex.fao.org/docs/pdf/tha200834.pdf>.
- [49] *Thailand Country Climate and Development Report*, Washington, DC, USA: World Bank Group, 2025, <https://documents1.worldbank.org/curated/en/099063025043513963/pdf/P507208-2e39fbbd-4d16-4660-a7eb-9c99c88864f0.pdf>.
- [50] Pollution Control Department, "National Solid Waste Management Master Plan (2016–2021)," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2016.
- [51] Pollution Control Department, "National Action Plan on Waste Management (Phase II, 2022–2027)," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2022.
- [52] "Waste Framework Directive." European Commission, http://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en.
- [53] M. Naghel, A. Farhi, and A. Redjem, "Household Waste Management Challenges: The Case of M'sila, Algeria," *Engineering, Technology & Applied Science Research*, vol. 12, no. 3, pp. 8675–8682, June 2022, <https://doi.org/10.48084/etasr.4925>.
- [54] T. Pudcha, A. Phongphiphat, and S. Towprayoon, "Greenhouse Gas Mitigation and Energy Production Potentials from Municipal Solid Waste Management in Thailand Through 2050," *Earth Systems and Environment*, vol. 7, no. 1, pp. 83–97, July 2022, <https://doi.org/10.1007/s41748-022-00323-z>.
- [55] *Singapore's First Biennial Transparency Report 2024*, Singapore: National Environment Agency, 2024, <https://www.nea.gov.sg/docs/default-source/cmd-documents/ghg-documents/singapore%27s-first-biennial-transparency-report-2024.pdf>.
- [56] P. S. Michel Devadoss, P. Agamuthu, S. B. Mehran, C. Santha, and S. H. Fauziah, "Implications of municipal solid waste management on greenhouse gas emissions in Malaysia and the way forward," *Waste Management*, vol. 119, pp. 135–144, Jan. 2021, <https://doi.org/10.1016/j.wasman.2020.09.038>.
- [57] Pollution Control Department, "Report on municipal solid waste composition in Thailand 2021," *Ministry of Natural Resources and Environment*, Bangkok, Thailand, 2021.