

Economic Activity and Provincial Solid Waste Generation in Thailand: Evidence from Satellite-Derived Spatial Analysis

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Abstract

Background and Objectives: Rapid urbanization, economic growth, and changing consumption patterns have increased provincial solid waste generation in Thailand, while waste-management capacity remains uneven across provinces. Existing studies often rely on aggregate statistics or localized case studies, limiting understanding of the spatial interdependence underlying waste dynamics. Recent advances in geospatial technologies allow satellite-derived indicators, such as nighttime lights, land-surface temperature, urbanization measures, and precipitation, to be used as spatial proxies for economic activity, environmental conditions, and human pressure. This study investigates the spatial interconnections between satellite-derived indicators and provincial solid waste generation across Thailand.

Methodology: The study uses provincial solid waste data from the 2024 Annual Report of the Ministry of Natural Resources and Environment and satellite-derived indicators processed through Google Earth Engine. Spatial analysis, including quartile mapping, spatial autocorrelation, and spatial clustering, is applied to examine spatial patterns and dependence. A structural equation model is then used to assess the influence of satellite-derived indices on provincial solid waste generation.

Key Findings: The results show that provincial solid waste generation in Thailand is spatially clustered and strongly shaped by geographic context. Satellite-derived indicators, particularly socioeconomic activity, urbanization, and daytime land-surface temperature are positively associated with solid waste generation. In contrast, precipitation shows a modest negative association, suggesting that rainfall may reflect broader climatic and geographic conditions rather than directly intensifying waste generation. The structural equation model indicates that satellite-derived indices collectively explain a substantial share of provincial variation in solid waste generation.

Policy Implications: The findings support the use of spatially differentiated waste-management policies that prioritize provinces with high urban, economic, and thermal intensity. Satellite-based monitoring systems can help improve real-time decision-making, infrastructure planning, and provincial waste-management strategies. Policymakers should integrate urban planning, industrial zoning, and climate-responsive approaches to mitigate solid-waste pressures in rapidly developing areas.

Keywords: Satellite-derived Indicators; Solid Waste Generation; Spatial Analysis; Structural Equation Model

JEL Classification Codes: Q53; R11; O18; C21; Q56

1. Introduction

Solid waste generation remains a major environmental and policy challenge across both developed and developing countries. Even in developed economies with established recycling systems and environmental regulations, waste volumes remain persistently high. Developing countries face greater difficulties because constraints in infrastructure, finance, human resources, and public awareness often limit the effectiveness of waste-management systems (Shukri & Jayasena, 2024). These limitations reduce management efficiency and may lead to waste accumulation and illegal dumping, thereby intensifying environmental degradation (Jawjit et al., 2024; Shukri & Jayasena, 2024).

In Southeast Asia, rapid urbanization, tourism expansion, mass production of single-use goods, and economic growth have outpaced waste-management capacity. At the same time, geographic, economic, climatic, and demographic heterogeneity has generated substantial spatial variation in waste generation and management performance. This pattern suggests that waste is not merely a quantitative issue, but a multidimensional problem shaped by local economic, social, and environmental conditions (Shukri & Jayasena, 2024).

Thailand reflects these challenges (Khaw-ngern et al., 2021). Provincial solid waste has increased alongside economic growth, tourism development, and changing consumption patterns (Ittiravivongs, 2012; Pumpinyo & Nitivattananon, 2014). Although national policies, including circular economy initiatives and plastic-reduction measures, have been introduced, spatial disparities remain. Some provinces have stronger infrastructure and administrative capacity, while others continue to experience high daily waste generation and substantial untreated residual waste (Jawjit et al., 2024; Pongpunpurt et al., 2022).

Provincial characteristics, including income levels, demographic structure, population density, land area, and land-use patterns, are expected to influence waste generation (Fraternali et al., 2024). Advances in geospatial technologies now allow researchers to integrate satellite-derived indicators, such as nighttime lights, land-surface temperature, and climate variables, to better capture spatial interactions between economic activity, environmental processes, and waste generation (Karimi et al., 2023). However, most existing studies rely on national aggregates or localized case analyses (Balilo et al., 2023), with limited attention to spatial interdependence, despite evidence that waste dynamics are influenced by neighboring regions (Khamkeo et al., 2021; Pasukphun et al., 2019). A more comprehensive understanding of Thailand's waste challenge therefore requires moving beyond aggregate analysis toward an explicit examination of underlying spatial structures (Karimi et al., 2023).

Building on the waste-management challenges in Thailand and the gaps identified in the existing literature, this study investigates the spatial interconnections between satellite-derived indicators and provincial solid waste generation across Thailand. Specifically, it examines how satellite-derived indices reflect economic activity, urbanization, environmental conditions, and climatic exposure, and how these factors are associated with provincial patterns of solid waste generation.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the conceptual framework. Section 4 describes the methods and data. Section 5 presents and discusses the empirical results. Section 6 concludes the study, and Section 7 provides policy implications.

2. Literature Review

2.1 Use of Satellite-Derived Indicators in Economic Studies

The use of satellite-derived data in economic research has expanded rapidly since the early 2000s, reflecting both the limitations of traditional economic statistics and advances in big-data technologies (Donaldson & Storeygard, 2016). In many developing and remote areas, conventional socioeconomic data are often incomplete, infrequently updated, or spatially aggregated, which restricts rigorous empirical analysis. Satellite imagery provides a consistent, high-frequency, and spatially granular alternative that enables researchers to capture economic dynamics that are difficult to observe using standard data sources.

A growing body of literature validates satellite-derived indicators as reliable proxies for economic activity across diverse contexts. Nighttime light intensity from Visible Infrared Imaging Radiometer Suite (VIIRS) data is widely used to reflect economic activity, infrastructure development, and socioeconomic status, based on the premise that brighter areas correspond to higher economic density and industrialization (Dasgupta, 2022; Prasertsoong & Puttanapong, 2022). Thermal indicators from Moderate Resolution Imaging Spectroradiometer (MODIS), including daytime and nighttime land-surface temperatures, are closely associated with industrial concentration, urban expansion, climate stress, and public-health-related economic impacts (Dissanayake et al., 2019; Prasertsoong & Puttanapong, 2025; Puttanapong & Lim, 2024). Similarly, precipitation indices derived from Climate Hazards Group InfraRed Precipitation with Station data are used to examine agricultural productivity, energy generation, and economic vulnerability to climate shocks, although their effects vary across geographic and institutional contexts (Barrios et al., 2010; Damania et al., 2020; Puttanapong & Lim, 2024). Collectively, these indicators enable multidimensional and spatially explicit analyses of economic processes, making them particularly useful for research in data-constrained environments.

2.2 Theoretical Framework of Solid Waste Generation

Solid waste generation can be conceptualized as a spatially embedded outcome of production, consumption, and material flows within the economy. As income, population concentration, urbanization, industrial activity, and service intensity increase, post-consumer and post-production residuals are also expected to rise. However, waste generation is not determined solely by economic scale; it is also shaped by disposal incentives and institutional arrangements. Empirical evidence shows that waste demand responds differently to pricing systems, including container-based fees, subscription systems, bag-based charges, and other unit-based pricing mechanisms, with elasticity depending on policy design and implementation (Bel & Gradus, 2016).

In Thailand, provincial solid waste pricing is largely based on flat or differentiated flat fees rather than unit-based pricing, implying a near-zero marginal cost for additional disposal. This weakens incentives for source reduction and makes short-run waste behavior relatively price-inelastic. Consequently, cross-provincial variation in waste generation is more likely to reflect structural conditions, such as urban intensity, socioeconomic activity, industrial concentration, land-use patterns, and environmental context, than direct behavioral responses to disposal prices.

This framework also justifies the provincial scale of analysis and the use of satellite-derived indicators. Although more disaggregated data may capture localized behavior, Thailand's waste-management system is nationally guided under the Ministry of Interior and operationally implemented by local administrative organizations, making provincial analysis relevant for both provincial and national planning. Satellite-

derived indicators provide a spatially explicit layer of evidence by capturing observable consequences of human activity and environmental pressure. Nighttime lights, urbanization indices, land-surface temperatures, and precipitation do not directly measure waste generation; rather, they proxy the location-specific intensity of economic activity, built-up expansion, anthropogenic heat, climatic exposure, and waste-related operating conditions.

The latent satellite-derived index in this study is therefore interpreted as an integrated measure of anthropogenic and environmental pressures embedded in the provincial waste-generation system. The model is best viewed as a supply-side spatial screening tool for identifying waste-generation pressure, prioritizing infrastructure investment, and supporting provincial waste planning, rather than as a behavioral model for evaluating demand-side pricing policies such as Pay-as-You-Throw schemes. It also supports broader policy instruments, particularly extended producer responsibility, product design for the environment, take-back systems, recyclability, reuse, and reduced dependence on virgin materials (Walls, 2006), consistent with the principle that prices across the product life cycle should reflect marginal social costs (Braathen, 2004).

2.3 Satellite-Derived Indicators in Solid Waste Management Studies

The expanding application of satellite remote sensing in solid waste management has generated strong empirical evidence of its capacity to reveal spatial patterns of waste generation, disposal, and related environmental externalities. Satellite-derived indicators enable the identification of both formal landfills and informal dumping sites at spatial scales that conventional field surveys cannot easily achieve (Naibbi & Umar, 2017; Kathambi & Ogutu, 2022). By integrating satellite imagery with GPS observations and topographical data, prior studies have detected spatial clustering of disposal sites, assessed proximity to environmentally sensitive areas, and identified discrepancies between reported and actual waste practices (Naibbi & Umar, 2017). The increasing availability of open-access satellite data further facilitates temporal analysis, allowing researchers to monitor landfill expansion and land-use changes associated with waste accumulation (Fraternali et al., 2024; Karimi et al., 2023).

Recent research shows that different satellite-derived features capture complementary dimensions of waste-related processes. Spectral signatures, vegetation stress indicators, and surface temperature anomalies provide indirect evidence of landfill presence and degradation intensity by reflecting soil disturbance, heat emissions, and ecosystem stress (Fraternali et al., 2024). Advances in deep learning using very high-resolution imagery have improved detection accuracy in heterogeneous landscapes and have outperformed conventional classification methods (Niu et al., 2022). However, limitations remain, including reduced performance under occlusion, lighting variability, and complex land-cover conditions, which constrain reliable object-level identification (Abdu & Noor, 2022). These methodological constraints are compounded by the uneven geographic distribution of studies, which remain concentrated mainly in Asia and Europe, limiting broader generalization (Karimi et al., 2023).

At the provincial scale, global applications often prioritize large-scale landfill detection and land-use monitoring, whereas studies in Asia tend to emphasize informal dumping, rapid urban expansion, and waste-related environmental stress in densely populated settings (Karimi et al., 2023). Evidence from Southeast Asia, including Thailand, highlights the value of satellite approaches in revealing spatial inequalities in waste distribution and management capacity, particularly where official statistics are

fragmented or incomplete (Kathambi & Ogutu, 2022; Naibbi & Umar, 2017). Nevertheless, Thailand's complex land-use patterns, seasonal climatic variability, and heterogeneous waste composition continue to challenge detection accuracy. These conditions underscore the need for context-specific calibration and stronger integration of satellite-derived indicators with socioeconomic and administrative data in future assessments.

3. Conceptual Framework

Based on the review of relevant literature, this study develops a conceptual framework that integrates satellite-derived indicators to analyze the spatial relationships and influencing factors associated with provincial solid waste generation in Thailand. The framework illustrates how remotely sensed socioeconomic, urban, environmental, and climatic indicators can be used to explain provincial variation in solid waste generation.

The independent variables consist of five satellite-derived indices: the socioeconomic index, urbanization index, daytime land-surface temperature index, nighttime land-surface temperature index, and precipitation index. These indicators capture different dimensions of anthropogenic and environmental pressure, including economic activity, built-up expansion, thermal intensity, and climatic exposure. The dependent variable is annual provincial solid waste generation. The conceptual framework is presented in Figure 1.

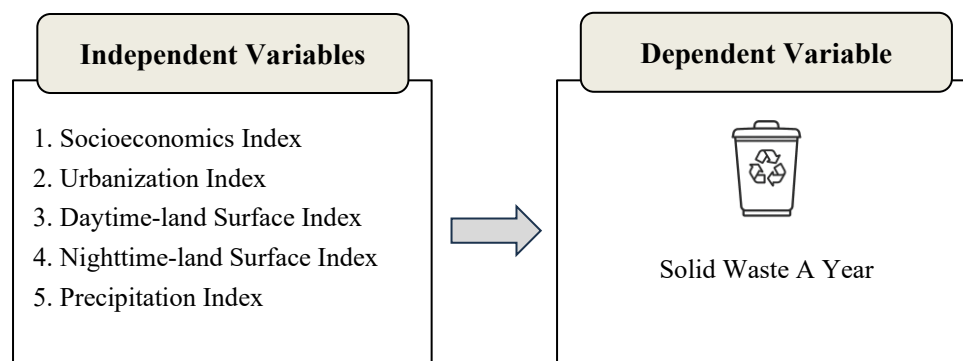


Figure 1. Conceptual Framework of the Study

Source: Authors' compilation.

Note: The satellite-derived indicators represent spatial proxies for economic activity, urbanization, environmental conditions, and climatic exposure. Annual solid waste generation is measured at the provincial level.

4. Methods and Data

4.1 Research Scope

This study adopts a quantitative research design using secondary spatial datasets as the main source of analysis. The empirical scope covers all 77 provinces of Thailand. The analysis consists of two main components: (1) an examination of the spatial linkages between satellite-derived indicators and provincial solid waste generation, and (2) an assessment of the influence of satellite-derived indices on provincial solid waste generation. The findings are expected to support more systematic urban and environmental planning, particularly in strengthening pollution control and waste-management strategies at the provincial level.

4.2 Data Source

This study uses two main sources of secondary data: (1) the 2024 Annual Report of the Ministry of Natural Resources and Environment and (2) satellite-derived datasets processed through Google Earth Engine. The annual solid waste data were obtained from the Ministry of Natural Resources and Environment, while the satellite-derived indicators were extracted and processed through Google Earth Engine as the geospatial analytical platform. All satellite-derived indicators were aggregated using weighted annual averages for 2024 to ensure temporal consistency and to reduce short-term fluctuations caused by atmospheric conditions, seasonal variation, and cloud contamination. The analysis was conducted at the provincial level across all 77 provinces of Thailand.

The satellite-derived variables were constructed from multiple remote-sensing products to capture different dimensions of economic activity, urban intensity, environmental conditions, and climatic exposure. The socioeconomic index was derived from Visible Infrared Imaging Radiometer Suite nighttime light imagery, which serves as a proxy for economic density, infrastructure intensity, and human activity. The urbanization index was generated from satellite-derived built-up land characteristics to reflect urban expansion and settlement concentration. The daytime and nighttime land-surface temperature indices were retrieved from Moderate Resolution Imaging Spectroradiometer thermal products, while the precipitation index was obtained from Climate Hazards Group InfraRed Precipitation with Station data.

Several indices are reported as unitless because they represent standardized spatial intensity measures rather than direct physical quantities. Detailed descriptions of the variables, units, and data sources are presented in Table 1.

Table 1. Variable Descriptions and Data Sources

Variables	Unit	Sources
Annual Solid Waste Generation	Ton	Ministry of Natural Resources and Environment
Socioeconomics Index	Unitless	VIIRS Nighttime Light via Google Earth Engine
Urbanization Index	Unitless	Built-up Land Index via Google Earth Engine
Daytime Land-surface temperature Index	Degree Celsius	MODIS Land Surface Temperature via Google Earth Engine
Nighttime Land-surface temperature Index	Degree Celsius	MODIS Land Surface Temperature via Google Earth Engine
Precipitation Index	Millimeter/Year	CHIRPS Climate Data via Google Earth Engine

Source: Authors' compilation.

Note: VIIRS = Visible Infrared Imaging Radiometer Suite; MODIS = Moderate Resolution Imaging Spectroradiometer; CHIRPS = Climate Hazards Group InfraRed Precipitation with Station data.

4.3 Analysis Procedure

To address the research objectives, the analytical procedures are organized into three main stages: distribution diagnosis and descriptive analysis, spatial association analysis, and structural equation modeling.

First, distribution diagnosis and descriptive analysis were conducted as preliminary steps before the main empirical analysis. The distributional properties of the variables were assessed using the Shapiro–Wilk test, which is suitable for relatively small sample sizes (Hanusz et al., 2016). The results of the distributional test informed the selection of descriptive statistics. If the variables followed a normal distribution, mean values and standard deviations were used as the main descriptive measures. If the variables deviated from normality, median values and interquartile ranges were used to

summarize the data. This approach helps ensure that the descriptive statistics are robust to outliers and skewed distributions.

Second, spatial autocorrelation and spatial clustering analyses were used to examine the spatial linkages between satellite-derived indices and provincial solid waste generation in Thailand. Spatial autocorrelation analysis, based on Moran's I, was applied to assess whether similar values are spatially clustered across neighboring provinces (Moran, 1950). Spatial clustering analysis, based on the Getis–Ord statistic, was then used to identify areas with statistically significant clusters of high or low values (Getis & Ord, 1992). Together, these methods help reveal the extent to which solid waste generation and satellite-derived indicators are spatially dependent across provinces.

Spatial autocorrelation analysis was conducted using Moran's I to assess whether similar values are spatially clustered across neighboring provinces. Moran's I is specified as follows:

$$I = \frac{N}{W} \frac{\sum_i \sum_j w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2} \quad (1)$$

where N denotes the number of spatial units, which in this study refers to provinces; x_i denotes the value of the variable in province (i); x_j denotes the value of the variable in province j; $\bar{x}$ denotes the mean value across all provinces; w_{ij} denotes the spatial weight defined by distance; and W denotes the sum of all spatial weights.

Spatial clustering was then examined using the Getis–Ord statistic to identify areas with statistically significant clusters of high or low values. The Getis–Ord statistic is specified as follows:

$$G_i^* = \frac{\sum_j w_{ij} x_j - \bar{X} \sum_j w_{ij}}{S \sqrt{\frac{[n \sum_j w_{ij}^2 - (\sum_j w_{ij})^2]}{n-1}}} \quad (2)$$

where n denotes the number of spatial units; S denotes the standard deviation across provinces; x_j denotes the value of the variable in province j; $\bar{X}$ denotes the mean value across all provinces; and w_{ij} denotes the spatial weight defined by distance.

Third, structural equation modeling was used to assess the influence of satellite-derived indices on provincial solid waste generation. SEM allows the simultaneous estimation of multiple relationships, helps reduce multicollinearity concerns, and provides flexibility in model adjustment compared with conventional regression techniques (Perry et al., 2015; Sánchez et al., 2005). The estimation method was selected based on the distributional properties of the data. Ordinary Least Squares was used when normality assumptions were satisfied, while Maximum Likelihood Estimation was applied under non-normal conditions.

The model consists of two components: the measurement model and the structural model. The measurement model specifies the relationships between the observed satellite-derived variables and the latent satellite-derived index. The structural model then estimates the relationship between the latent satellite-derived index and annual provincial solid waste generation.

The measurement model is specified as follows:

$$\ln(NTL)_i = \omega_i(SATELLITE\ INDEX) + e_i \quad (3)$$

$$\ln(URBAN)_i = \omega_i(SATELLITE\ INDEX) + e_i \quad (4)$$

$$\ln(DAYTEMP)_i = \omega_i(SATELLITE\ INDEX) + e_i \quad (5)$$

$$\ln(NIGHTTEMP)_i = \omega_i(SATELLITE\ INDEX) + e_i \quad (6)$$

$$\ln(PRECIPITATION)_i = \omega_i(SATELLITE\ INDEX) + e_i \quad (7)$$

where the observed variables consist of the socioeconomic index (*NTL*), urbanization index (*URBAN*), daytime land-surface temperature index (*DAYTEMP*), nighttime land-surface temperature index, (*NIGHTTEMP*) and precipitation index (*PRECIPITATION*); the latent variable is the satellite-derived index (*SATELLITE INDEX*); the estimated parameters (ω_i) represent the factor loadings; and the disturbance terms (e_i) capture unexplained variation in each observed indicator.

The structural model is specified as follows:

$$\ln(TRASH)_i = \beta_i(SATELLITE\ INDEX) + v_i \quad (8)$$

where annual provincial solid waste generation is the observed dependent variable; the satellite-derived index is the latent explanatory variable; the estimated parameter captures the influence of the latent index on solid waste generation; and the disturbance term represents unexplained variation in provincial solid waste generation.

After estimating the model, adjustment procedures were applied when inconsistencies were found between the estimated model and the empirical data. Additional covariance paths were specified where theoretically and empirically justified to improve model fit and to obtain a more coherent representation of the underlying data structure (Perry et al., 2015).

5. Results and Discussion

Following data compilation and preliminary distributional testing, the Shapiro–Wilk results indicate that most variables are not normally distributed. Accordingly, median values and interquartile ranges are used to summarize central tendencies and dispersion. The median annual provincial solid waste generation is approximately 226,440 tons. Most variables have median values substantially below their corresponding means, indicating pronounced right-skewness and the concentration of solid waste generation in a subset of provinces with disproportionately high annual waste loads. The results also reveal considerable dispersion across provinces, reflecting substantial spatial inequality in solid waste generation. This spatial heterogeneity is consistent with the variation captured by satellite-derived urbanization indicators, reinforcing the role of structural provincial differences in shaping waste intensity.

Environmental indicators, measured through daytime and nighttime land-surface temperature indices, show median temperatures of 30.29°C and 22.98°C, respectively. The relatively low variability in these measures suggests limited spatial variation in thermal intensity across provinces. The precipitation index, with a median of 132.12 mm/hr and low dispersion, indicates relatively stable climatic conditions, although precipitation may still influence waste generation through seasonal disruptions, operational constraints, and changes in consumption behavior. Detailed statistics are reported in Table 2.

Table 2. Descriptive Statistics and Distribution Diagnosis Results

	Mean	Std. Dev.	Median	IQR	Shapiro-Wilk
Solid Waste A Year	322,834.70	511,167.90	226,440.00	201,780.00	0.3647***
Socioeconomics Index	16.58	10.03	12.96	4.73	0.6201***
Urbanization Index	334.91	539.24	183.01	266.01	0.5002***
Daytime-land Surface Index	30.16	1.84	30.29	0.04	0.9658**
Nighttime-land Surface Index	22.95	1.14	22.98	1.40	0.9906
Precipitation Index	143.10	38.11	132.12	35.08	0.7911***

Source: Authors' calculations.

Note: IQR = interquartile range. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

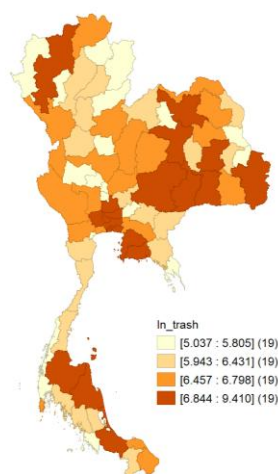
5.1 Association Between Satellite-Derived Indices and Provincial Solid Waste Generation

This section presents the spatial analysis by integrating three components: spatial quantile distribution in Panel A, spatial clustering in Panel B, and spatial autocorrelation in Panel C.

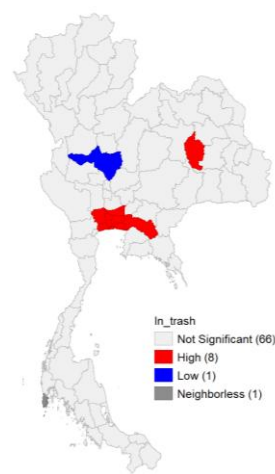
The spatial quantile distribution indicates pronounced provincial variation in solid waste generation. Higher waste-generation intensity is observed in several provinces with large urban populations, strong economic activity, and dense service or industrial functions, including Chiang Mai, Ubon Ratchathani, Nakhon Ratchasima, Bangkok, Ayutthaya, Chonburi, Rayong, Surat Thani, Nakhon Si Thammarat, and Krabi. Spatial clustering analysis further shows that high-intensity waste areas are concentrated mainly in the central region, particularly Bangkok, Chachoengsao, Samut Sakhon, and Samut Songkhram.

In contrast, provinces such as Nakhon Sawan record comparatively lower waste generation relative to neighboring areas. The spatial autocorrelation result confirms a positive association, with a Moran's I value of 0.233, indicating that provincial solid waste generation is not randomly distributed but shaped by spatial dependence. This evidence highlights the importance of geographic context in explaining the distribution and magnitude of solid waste challenges across Thailand, as illustrated in Figure 2.

(A)



(B)



(C)

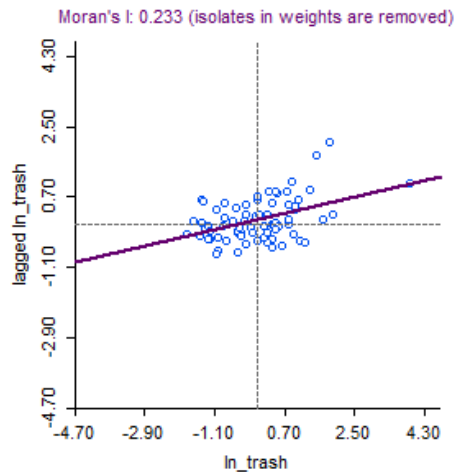


Figure 2. Spatial Association and Clustering of Provincial Solid Waste Generation

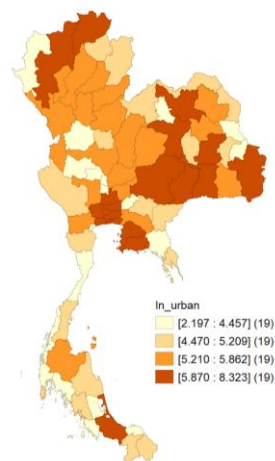
Source: Authors' calculations.

Note: Panel A presents the spatial quantile distribution, Panel B presents spatial clustering, and Panel C presents spatial autocorrelation.

Figure 3 presents the spatial quantile distribution of the urbanization index across Thailand. Urban intensity is more evident in provinces with larger settlement concentrations, higher population density, and stronger built-up development, including Chiang Mai, Ubon Ratchathani, Nakhon Ratchasima, Bangkok, Ayutthaya, and Songkhla. The highest levels of urban development are clustered in the central region, particularly Bangkok and its neighboring provinces.

The spatial autocorrelation analysis indicates a positive association between the urbanization index and provincial solid waste generation, with a coefficient of 0.231. This result suggests a clear co-movement pattern, whereby provinces with higher levels of urbanization tend to generate larger volumes of solid waste.

(A)



(B)



(C)

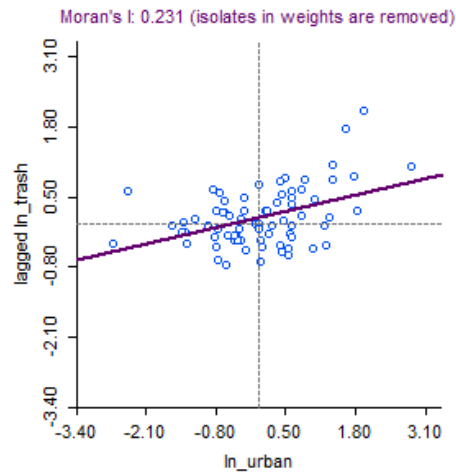


Figure 3. Spatial Association and Clustering Between the Urbanization Index and Provincial Solid Waste Generation

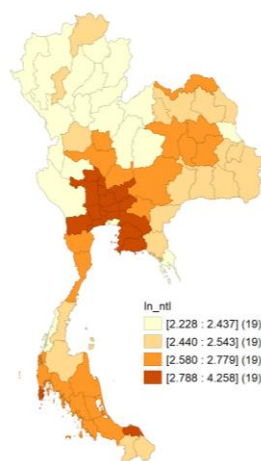
Source: Authors' calculations.

Note: Panel A presents the spatial quantile distribution, Panel B presents spatial clustering, and Panel C presents spatial autocorrelation.

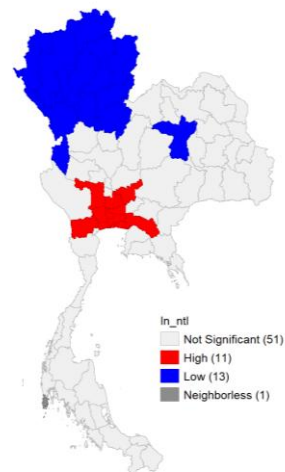
Figure 4 presents the spatial distribution of socioeconomic activity across Thailand. Economic intensity is concentrated in the central and eastern regions, particularly in Bangkok, Pathum Thani, Nonthaburi, Ratchaburi, Chachoengsao, Chonburi, and Rayong. In contrast, several northern provinces, including Mae Hong Son, Lampang, and Phayao, exhibit relatively lower socioeconomic intensity.

Spatial autocorrelation analysis confirms significant clustering of high socioeconomic activity in the central and eastern regions, while low-intensity clusters are more evident in parts of the northern region. The socioeconomic index is positively associated with provincial solid waste generation, with a coefficient of 0.236. This indicates that provinces with stronger economic activity tend to generate larger volumes of solid waste.

(A)



(B)



(C)

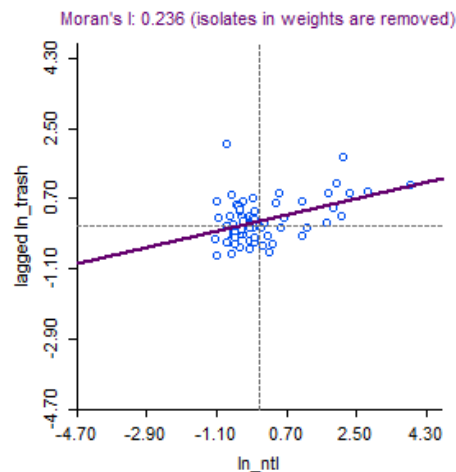


Figure 4. Spatial Association and Clustering Between the Socioeconomic Index and Provincial Solid Waste Generation

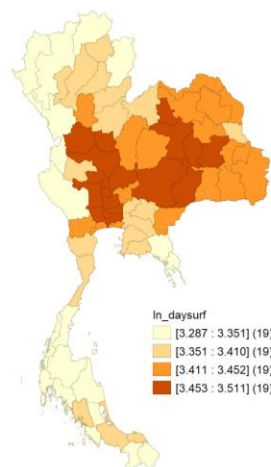
Source: Authors' calculations.

Note: Panel A presents the spatial quantile distribution, Panel B presents spatial clustering, and Panel C presents spatial autocorrelation.

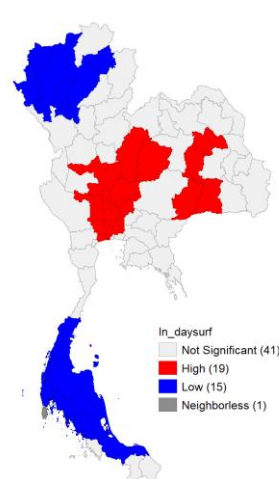
The daytime land-surface temperature index indicates elevated thermal intensity in several provinces, including Nong Bua Lamphu, Khon Kaen, Buriram, Surin, Kalasin, Kamphaeng Phet, Nakhon Sawan, Chai Nat, Sing Buri, Ang Thong, Bangkok, and surrounding areas. Spatial clustering results show that high-temperature concentrations are primarily located in the central region and parts of the lower northeastern region, while the northern and southern regions form relatively lower-intensity clusters.

A positive correlation coefficient of 0.201 further indicates that higher daytime surface temperatures are associated with the spatial distribution of provincial solid waste generation. This relationship may reflect the role of built-up density, infrastructure concentration, reduced vegetation cover, and intensive daytime human activity in shaping both thermal conditions and waste-generation patterns, as shown in Figure 5.

(A)



(B)



(C)

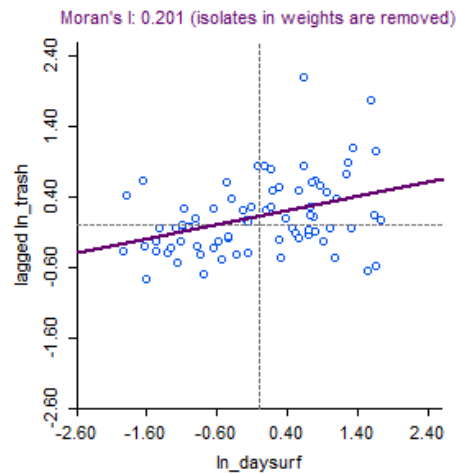


Figure 5. Spatial Association and Clustering Between the Daytime Land-Surface Temperature Index and Provincial Solid Waste Generation

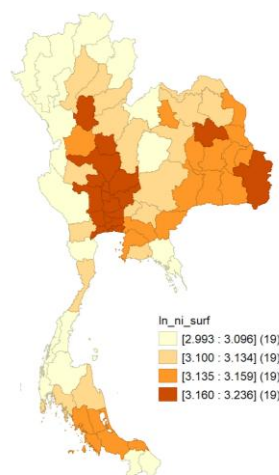
Source: Authors' calculations.

Note: Panel A presents the spatial quantile distribution, Panel B presents spatial clustering, and Panel C presents spatial autocorrelation.

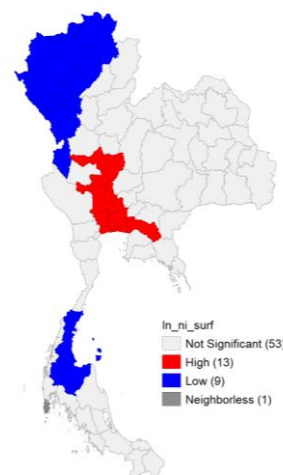
The nighttime land-surface temperature index shows elevated thermal zones extending from the lower northern region to the central region, particularly in Phichit, Nakhon Sawan, Lopburi, Saraburi, Ayutthaya, Pathum Thani, and Bangkok, with additional hotspots in Kalasin and Ubon Ratchathani. Spatial clustering analysis further indicates that high nighttime temperature intensity is concentrated along the lower northern to central corridor.

Rather than attributing this pattern solely to manufacturing activity, the result may reflect a combination of built-up surfaces, retained urban heat, transportation corridors, logistics activity, and continued nighttime economic functions. The spatial association between nighttime land-surface temperature and provincial solid waste generation yields a positive coefficient of 0.207. This suggests that provinces with higher nighttime thermal intensity tend to exhibit higher levels of solid waste generation, as shown in Figure 6.

(A)



(B)



(C)

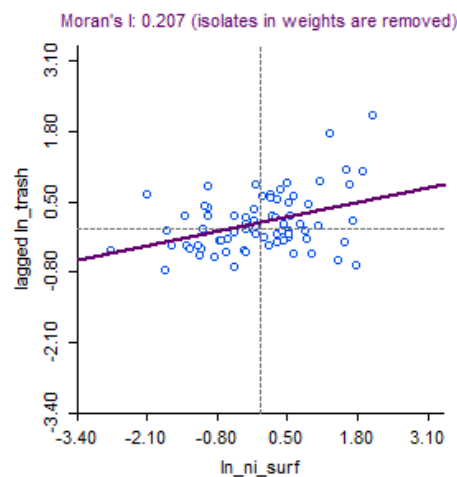


Figure 6. Spatial Association and Clustering Between the Nighttime Land-Surface Temperature Index and Provincial Solid Waste Generation

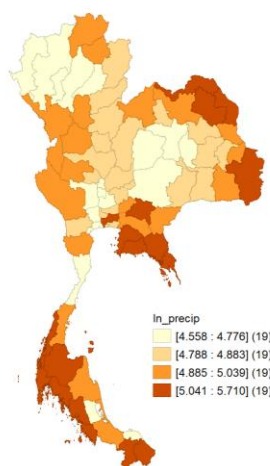
Source: Authors' calculations.

Note: Panel A presents the spatial quantile distribution, Panel B presents spatial clustering, and Panel C presents spatial autocorrelation.

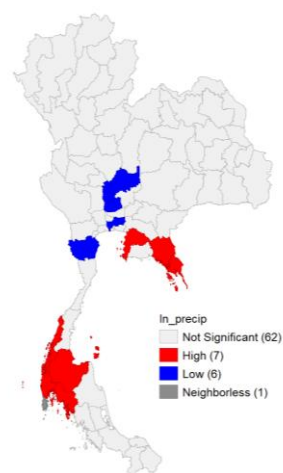
Figure 7 presents the spatial distribution of the precipitation index across Thailand. Higher precipitation intensity is concentrated in several border, eastern, and southern provinces, including Nong Khai, Bueng Kan, Sakon Nakhon, Ubon Ratchathani, Prachinburi, Chonburi, Chanthaburi, Trat, Rayong, Samut Prakan, Ranong, Phang Nga, and Krabi. Spatial clustering analysis shows that the eastern and southern regions form distinct high-precipitation clusters, while lower precipitation intensity is observed in provinces such as Phetchaburi, Bangkok, Saraburi, Ayutthaya, and Pathum Thani.

The spatial association between precipitation and solid waste generation yields a coefficient of -0.108, indicating a modest inverse relationship. This suggests that precipitation may not directly intensify solid waste generation at the provincial scale, but may instead reflect broader climatic and geographic conditions that interact with waste collection, settlement patterns, and local economic structures.

(A)



(B)



(C)

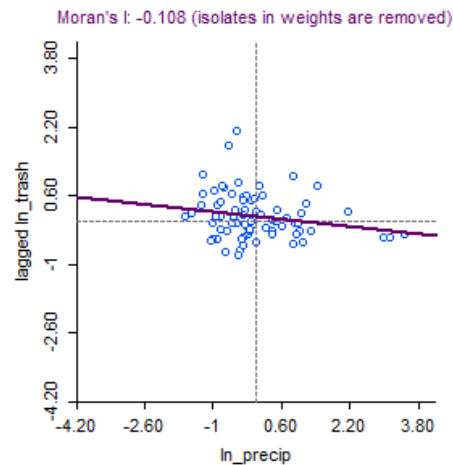


Figure 7. Spatial Association and Clustering Between the Precipitation Index and Provincial Solid Waste Generation

Source: Authors' calculations.

Note: Panel A presents the spatial quantile distribution, Panel B presents spatial clustering, and Panel C presents spatial autocorrelation.

5.2 Influence of Satellite-Derived Indices on Provincial Solid Waste Generation

The influence of satellite-derived indices on provincial solid waste generation was assessed using structural equation modeling. The initial estimation showed inconsistencies between the estimated model and the empirical relationships, indicating the need for model adjustment. After model adjustment, all goodness-of-fit indices satisfied the recommended thresholds, suggesting that the adjusted model provides a more coherent representation of the underlying data structure, as reported in Table 3.

Table 3. Model Fit Before and After Adjustment

Goodness of Fit Indexes	Threshold	Before Adjustment	Remark	After Adjustment	Remark
Chi-squared (df.)	-	118.5330 (9)	Not Passed	3.4350 (3)	Passed
Chi-squared (Prob.)	> 0.05	0.0000	Not Passed	0.3293	Passed
Relative Chi-squared	< 2.00	13.1703	Not Passed	1.1450	Passed
CFI	> 0.95	0.5570	Not Passed	0.9980	Passed
RMSE	< 0.05	0.4000	Not Passed	0.0440	Passed
SRMR	< 0.05	0.1750	Not Passed	0.0480	Passed

Source: Authors' calculations.

Note: CFI = comparative fit index; RMSE = root mean square error; SRMR = standardized root mean square residual.

The estimated structural model shows standardized loadings ranging from -0.2996 to 0.6600 and R-squared values ranging from 0.0898 to 0.4357, all statistically significant. These results indicate that each observed satellite-derived indicator contributes meaningfully to the latent satellite-derived index and to the explanation of provincial solid waste generation, as reported in Table 4.

Collectively, the satellite-derived indices explain 73.90% of the variation in provincial solid waste generation across Thailand. The strongest effects arise from the daytime land-surface temperature index, socioeconomic index, and urbanization index, which account for 43.57%, 39.37%, and 39.26% of the variation, respectively. In contrast, nighttime land-surface temperature and precipitation indices exhibit

comparatively smaller, though still observable, effects, as shown in Table 4 and Figure 8.

Table 4. Structural Equation Estimation Results

		Loading	Std. Err.	R-squared
Structural Level Estimation				
Satellite Index	→ Solid Waste A Year	0.5505		0.3030
Measurement Level Estimation				
Socioeconomics Index	→ Satellite Index	0.6275	0.1196***	0.3937
Urbanization Index	→ Satellite Index	0.6266	0.1177***	0.3926
Daytime-land Surface Index	→ Satellite Index	0.6600	0.1169***	0.4357
Nighttime-land Surface Index	→ Satellite Index	0.4414	0.1327***	0.1949
Precipitation Index	→ Satellite Index	-0.2996	0.1507**	0.0898
Overall				0.7390

Source: Authors' calculations.

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

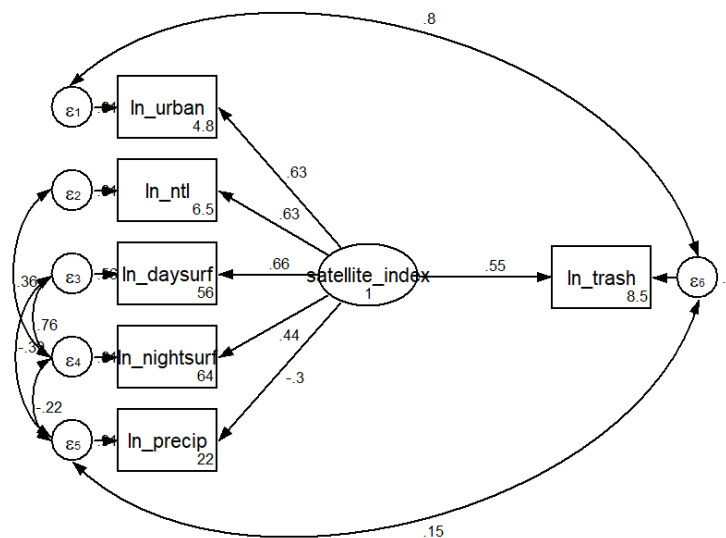


Figure 8. Structural Equation Estimation Results After Model Adjustment

Source: Authors' calculations.

Note: Standardized coefficients are reported.

The empirical results support the growing literature on the effectiveness of satellite-derived indicators in explaining spatially complex economic and environmental phenomena. Consistent with prior studies using nighttime lights, land-surface temperatures, and precipitation indices as proxies for economic density and climate-related pressures (Dissanayake et al., 2019; Donaldson & Storeygard, 2016; Prasertsoong & Puttanapong, 2022), urbanization, socioeconomic activity, and daytime temperature emerge as important predictors of provincial solid waste generation in Thailand. These findings also reinforce remote-sensing evidence that spatial clustering and location-specific dynamics are central to waste accumulation patterns (Kathambi & Ogutu, 2022; Naibbi & Umar, 2017). The strong explanatory power of thermal and urbanization indicators confirms their capacity to capture anthropogenic intensity and environmental stress associated with waste production.

These spatial-environmental relationships can be interpreted within a broader economic framework that incorporates institutional incentives and pricing mechanisms. Solid waste is a by-product of production and consumption, and its volume depends not only on economic scale and urban concentration but also on marginal disposal costs. Prior research shows that price elasticity varies across charging systems, such as container-based fees and unit pricing (Bel & Gradus, 2016). In Thailand, however, waste pricing is predominantly based on flat or differentiated flat fees, implying near-zero marginal disposal costs. This structure weakens incentives for waste reduction, resulting in relatively inelastic waste behavior. Consequently, cross-provincial variation is more strongly driven by structural economic activity, urban intensity, and environmental conditions than by price-based behavioral adjustments. Under such institutional settings, satellite-derived indicators serve as effective proxies for underlying economic and environmental pressures.

The institutional context further justifies the provincial scale of analysis. Although aggregation may mask micro-level heterogeneity, it aligns with Thailand's governance structure, where provincial solid waste management is nationally guided and locally implemented by local administrative organizations. This decentralized yet centrally regulated framework produces institutional consistency in pricing regimes and service provision across provinces. Provincial-level data therefore capture both spatial variation in economic activity and the policy environment shaping waste outcomes, making them suitable for evaluating nationwide waste-generation patterns.

While the findings confirm the value of satellite-based approaches, they also reveal important contextual nuances. Although previous studies have emphasized landfill-level spectral signatures and other remote-sensing indicators for waste detection and monitoring (Fraternali et al., 2024; Karimi et al., 2023), the present study finds that precipitation and nighttime land-surface temperature exert only modest effects on provincial solid waste generation. In particular, the precipitation index shows a weak negative association, suggesting that rainfall does not directly intensify waste generation at the provincial scale but may instead reflect broader climatic, geographic, and settlement conditions that interact with waste collection and local economic structures. These differences likely reflect Thailand's climatic variability, heterogeneous land-use patterns, and region-specific waste-management conditions.

Overall, the results highlight the need for context-specific calibration and demonstrate that satellite-derived indicators do not operate uniformly across settings, even though they remain valuable tools for linking observable environmental signals with institutional and economic structures in solid waste management.

6. Conclusions

This study examined the spatial interconnections between satellite-derived indicators and provincial solid waste generation across Thailand. Using provincial solid waste data and satellite-derived indicators processed through Google Earth Engine, the study applied spatial analysis and structural equation modeling to assess how socioeconomic activity, urbanization, land-surface temperature, and precipitation are associated with annual provincial solid waste generation.

The spatial analyses show that provincial solid waste generation in Thailand is strongly shaped by geographic context. High-intensity waste-generation clusters are concentrated mainly in economically dynamic and urbanized provinces, particularly in the central region. The results also indicate positive spatial associations between solid waste generation and satellite-derived indicators, especially the socioeconomic index,

urbanization index, and daytime land-surface temperature index. These findings confirm that satellite-derived indicators can serve as useful spatial proxies for human activity, built-up expansion, and environmental pressure.

The structural equation model further confirms the explanatory power of satellite-derived indicators. Collectively, the satellite-derived indices explain more than 70% of the variation in provincial solid waste generation. Among these indicators, daytime land-surface temperature, socioeconomic activity, and urbanization show the strongest contributions, while nighttime land-surface temperature and precipitation have comparatively smaller effects. The modest negative association between precipitation and solid waste generation suggests that climatic conditions may moderate, rather than directly intensify, provincial waste patterns.

Overall, the findings highlight the importance of spatial heterogeneity in explaining solid waste generation across Thailand. They also demonstrate the value of integrating remote-sensing indicators into evidence-based urban environmental management. By combining official waste statistics with satellite-derived spatial indicators, this study provides a useful framework for identifying waste-generation pressure, prioritizing provincial waste-management interventions, and supporting more targeted environmental planning.

7. Policy Implications

The findings highlight the need for spatially differentiated waste-management policies that account for provincial differences in economic activity, urbanization, environmental conditions, and climatic exposure. Since solid waste generation is concentrated in economically dynamic and highly urbanized provinces, policy interventions should prioritize areas with high waste-generation pressure, particularly provinces in the central region and other rapidly developing urban and tourism centers. These areas may require greater investment in waste collection systems, treatment facilities, recycling infrastructure, and monitoring capacity.

Satellite-derived indicators can also be incorporated into provincial waste-management planning. Indicators such as nighttime lights, built-up land intensity, and land-surface temperature provide useful spatial proxies for human activity, urban expansion, and environmental pressure. Integrating these indicators with official waste statistics can support real-time monitoring, early identification of high-pressure areas, and more efficient allocation of waste-management resources. Such an approach would help policymakers move beyond aggregate planning toward more targeted and evidence-based interventions.

The positive association between urbanization, socioeconomic activity, daytime land-surface temperature, and solid waste generation suggests that waste-management policy should be better integrated with urban planning, industrial zoning, land-use regulation, and climate-responsive infrastructure. Provinces experiencing rapid urban expansion should be encouraged to strengthen waste separation, collection coverage, recycling systems, and treatment capacity alongside urban development. Industrial and commercial zones should also be planned with adequate waste-management facilities to reduce pressure on municipal systems.

The results further suggest that economic and environmental policies should be coordinated across provincial boundaries. Since solid waste generation exhibits spatial dependence, waste-management challenges are not confined to individual provinces. Neighboring provinces, particularly those within the same urban, industrial, or tourism corridor, should coordinate waste planning, infrastructure investment, and monitoring

systems. This would help address spillover effects and improve the efficiency of regional waste-management strategies.

Finally, future research should extend the analysis by incorporating longitudinal satellite data, more disaggregated spatial units, behavioral factors, and machine-learning approaches. These extensions would help improve predictive accuracy, identify emerging waste-generation hotspots, and support more adaptive environmental governance. A stronger integration of satellite-derived data with administrative, socioeconomic, and waste-management information would provide a more comprehensive basis for evidence-based policy design.

8. Ethics Statement

This study used secondary data from publicly available sources and did not involve human participants, personal identifiable information, or primary data collection. Therefore, ethics committee approval was not required.

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