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Modeling the Socioeconomic Drivers of E-Waste Generation in Southeast Asia

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Abstract

Introduction: E-waste is increasing across Southeast Asia (SEA), yet comparative evidence on its socioeconomic factors remains limited. Prior research is dominated by single-country case studies and inconsistent measures, obscuring the relative roles of population, income, urbanization, and electricity access. This study harmonizes official statistics for 11 SEA countries—Brunei Darussalam, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, and Vietnam—to quantify these relationships.

Methods: Cross-sectional log-linear ordinary least squares (OLS) models were estimated with outcomes ln(total e-waste, million kg) and ln(e-waste per capita, kg/person), regressed on ln(population), ln(GDP per capita), urbanization (average annual rate, 2010–2023), and urban electricity access (0–1). Official datasets from the Global E-waste Monitor 2024, the World Bank, Worldometers, Asian Development Bank, and United Nations were harmonized and standardized. Robustness was assessed via variance corrections, residual diagnostics, multicollinearity tests, and leave-one-out refits.

Results: Total e-waste rises mainly with population and secondarily with income, while per-capita generation is driven by economic development rather than population density. Urbanization and electricity access show no independent effect once these are controlled. Diagnostic checks confirm the models' stability, with results robust across specifications and unaffected by single-country influence.

Conclusion: E-waste production in Southeast Asia is structurally shaped by demographic scale that drives aggregate volumes, while affluence explains per-capita intensity. Urbanization and electricity access, though often cited as modernization indicators, show no independent relationship once population and income are controlled. These findings establish a regional baseline for understanding and tracking e-waste drivers.

Keywords: Economic development, Electronic waste, Population density, Regression analysis, Socioeconomic factors

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Introduction

Electronic waste (e-waste)—discarded electrical and electronic equipment—is the world's fastest-growing waste stream, propelled by rapid innovation, planned obsolescence, and rising consumption (1-3). The Global E-waste Monitor 2024 (4) underscores the stakes: Improper handling releases an estimated 82.4 billion kilograms of CO_2-equivalents, 34.5 thousand kilograms of mercury, and 26 million kilograms of plastics containing brominated flame retardants, while squandering recoverable critical materials. These costs sharpen the urgency of circular-economy strategies grounded in sustainability, efficiency, and safety.

In Southeast Asia (SEA), rising device uptake and shortening replacement cycles are accelerating electronic waste generation. Yet comparative, policy-relevant evidence on its socioeconomic determinants remains limited. Most existing research consists of country-specific case studies, material-flow assessments, or descriptive surveys, often relying on simple correlations or local samples that cannot be generalized across heterogeneous economies. Recent work has examined proxies such as mobile subscriptions and internet penetration (5), but statistically validated, cross-country analyses remain scarce. Comparative discussions also tend to extrapolate from Organisation for Economic Cooperation and Development (OECD) contexts with strong institutions and near-universal electricity access—conditions that do not uniformly apply in Southeast Asia.

To fill this gap, the present study compiles a harmonized dataset for eleven SEA countries and estimates log–linear models for both total and per-capita e-waste, relating outcomes to population and income while taking urbanization and urban electricity access into account.

To enable cross-country comparability, the analysis applies a log-linear design that expresses demographic and economic influences on e-waste in elasticity form, distinguishing between scale effects linked to population and intensity effects linked to affluence. The objective was to quantify how these socioeconomic factors are associated with e-waste across Southeast Asia and, in doing so, to provide evidence to inform near-term planning—such as calibrating collection targets, sequencing the formalization of recycling, and prioritizing extended producer responsibility where income-driven growth in per-capita e-waste is most pronounced.

Materials and Methods

This research employed a cross-sectional quantitative approach to examine the socioeconomic factors influencing e-waste generation in 11 SEA nations.

Data sources and collection

Data for both independent and dependent variables were compiled from authoritative national and international sources to ensure accuracy and cross-country comparability. E-waste figures—total (million kilograms) and per capita (kilograms)—were primarily sourced from the Global E-waste Monitor 2024, the most comprehensive dataset on global e-waste (4). Where data were unavailable, the most recent estimates (e.g., 2023) were used and documented. GDP per capita (USD) was obtained from the World Bank (6) as a proxy for national wealth. Population data for 2023 were drawn from Worldometers (7). Average urbanization rates (2010–2023), reflecting long-term demographic shifts, were retrieved from the Asian Development Bank's Key Indicators Database (8). Urban electricity access rates, used to approximate infrastructure readiness and electronic consumption, were derived from the ASEAN Secretariat and UN-Habitat (9).

Data cleaning and preparation

Data were compiled in Microsoft Excel and imported into R (v. 4.5.1) using the readxl package. Variables were standardized, and highly skewed measures of e-waste, population, and GDP per capita were log-transformed to stabilize variance and allow elasticity interpretation. Missingness was reviewed at both variable and case levels; one incomplete observation was removed, and a limited rule-based imputation was applied (e.g., Singapore's urbanization = 100%, electricity access = 1.00). Outliers were screened using standardized z-scores ($|z| > 3$) and inspected before modeling. All processing was performed in R with *dplyr* for data management, ggplot2 for visualization, and car for diagnostics.

Data analysis

Structural Equation Modeling (SEM) and path analysis were initially considered to capture complex interrelationships among socioeconomic drivers. However, the dataset comprised only eleven cross-sectional observations, well below recommended thresholds for SEM (10,11). Prior studies note that SEM generally requires sample sizes of more than 200 to achieve stable estimates and avoid inflated fit indices (12,13). To mitigate risks of overfitting, a parsimonious log-linear multiple regression model was employed instead. Estimation was conducted in R using the linear modeling framework, specifying natural-logarithmic transformations of total e-waste in million kilograms and per-capita e-waste in kilograms per person as dependent variables, with predictors including natural-logarithmic population, natural-logarithmic GDP per capita, average annual urbanization rate, and urban electricity access. Robust inference was obtained using the heteroskedasticity-consistent covariance matrix estimator type three through the *sandwich* and *lmtest* packages. At the same time, diagnostic tests were implemented with the car package and visualization undertaken with *ggplot2*. This approach yields interpretable elasticities, supports robust inference under small-sample conditions (14), and permits diagnostic validation while clarifying the structural drivers of e-waste generation in the SEA.

Model specification

Two outcomes were analyzed in this study: *In(Total E-waste,mimmion kg)* and *In (E - waste per capita,kg / person)*. Predictors comprised *In (Population)*, *In (GDP per capita)* the average urbanization rate (2010–2023, percentage points), and urban electricity access (proportion, 0–1). This configuration permits interpretation of coefficients on logged predictors as elasticities and of coefficients on unlogged predictors as semi-elasticities.

For each outcome, cross-sectional log–linear ordinary least squares (OLS) models were estimated on the 11-country sample:

$$1n(EW_i) = \beta_0 + \beta_1 1n(Pop_i) + \beta_2 1n(GDPpc_i) + \beta_3(Urban_i) + \beta_4(Elec_i) + \varepsilon_i$$

$$1n(EWpc_i) = \gamma_0 + \gamma_1 1n(Pop_i) + \gamma_2 1n(GDPpc_i) + \gamma_3(Urban_i) + \gamma_4(Elec_i) + \upsilon_i$$

Where *i* indexes countries. The log specification separates scale effects (population) from intensity effects (income) and supports cross-country comparability.

Model estimation and diagnostic assessment

Model adequacy was evaluated through multiple diagnostic procedures. Variance behavior was examined via scale–location plots and a Breusch–Pagan screen (limited by n = 11). Where heteroskedasticity was evident or plausible, inference used the Heteroskedasticity-Consistent Covariance Matrix Estimator, type 3 (HC3), which is appropriate for small samples and high-leverage observations. Residual diagnostics assessed linearity, normality, and variance stability, while multicollinearity was tested with variance inflation factors (VIFs). Influence diagnostics (leverage, Cook's distance, studentized residuals) evaluated coefficient stability and outliers. Leave-one-out (LOO) refits further tested sensitivity to individual countries. Analyses were conducted in R using *lm*, *sandwich*, *lmtest*, *car*, *dplyr*, and *ggplot2*.

Results

This section first outlines data on total and per-capita e-waste across 11 Southeast Asian countries, along with GDP per capita, urbanization, and electricity access. It then presents regression results linking these factors to e-waste generation, followed by diagnostics and robustness checks assessing the stability and validity of the estimates.

Profile of E-waste and socioeconomic drivers in the SEA

As shown in Supplemental Figure 1 (Figure S1), GDP per capita in Southeast Asia spans a wide spectrum—from below USD 2,500 in Cambodia and Timor-Leste to above USD 30,000 in Brunei and around USD 60–67k in Singapore. Most economies show steady gains through 2012–2019, with clear downturns in 2020 consistent with the COVID-19 disruptions (notably Indonesia, Malaysia, the Philippines, Thailand, Vietnam, Cambodia, and Singapore), while Timor-Leste is a mild exception with a small uptick. Population sizes also vary widely—under 1.5 million in Brunei and Timor-Leste, about 5.8–5.9 million in Singapore, over 100 million in the Philippines and Vietnam, and nearly 300 million in Indonesia (Figure S2). Most countries continue to grow steadily, though Thailand has approached a demographic plateau around 2020.

Urbanization trends further highlight regional contrasts (Figure S3). Vietnam (2.06 pp/yr), Cambodia (1.88), and Lao PDR (1.74) recorded the fastest increases in urban population share, whereas Brunei Darussalam (0.49) and Singapore (0.07) showed the slowest growth. These patterns underscore how emerging economies are urbanizing more rapidly than their high-income counterparts, consistent with differing stages of demographic and economic transition. Urban electricity access (Figure S4) is generally high, with Brunei, Lao PDR, Malaysia, Singapore, Thailand, Timor-Leste, and Vietnam achieving full coverage. Cambodia (99%) and Indonesia (98%) are only slightly below, while the Philippines (91%) and Myanmar (63%) continue to face significant gaps in universal access.

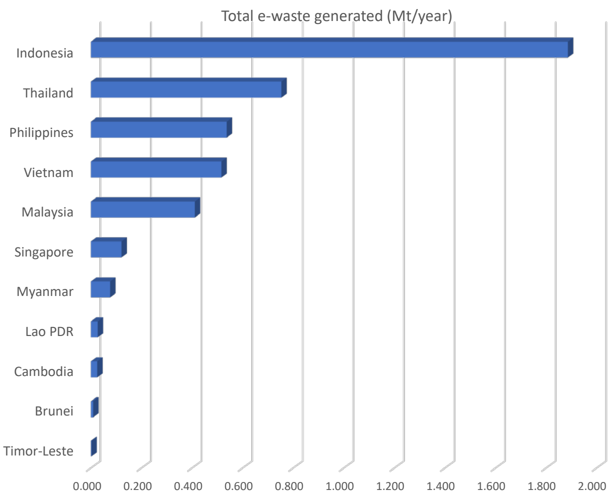

Figure 1. E-waste Totals (Annual Flows)

Figures 1 and 2 present complementary dimensions of the e-waste burden in Southeast Asia. Figure 1 reports total generation (Mt/year), which scales with population, ranging from 0.002 Mt (2 million kg/year) in Timor-Leste to 1.886 Mt in Indonesia. Figure 2 shows per-capita generation (kg/person/year), revealing income-related gradients: Cambodia, Myanmar, Timor-Leste, and Lao PDR generate < 5 kg/person/year, whereas Singapore exceeds 20 kg/person/year, and Brunei is approximately 20 kg/person/year.

Regression evidence on regional E-Waste drivers

The log-linear regression matrix (Table 1) provided strong explanatory power, accounting for nearly all of the variance in e-waste generation across the SEA (Adjusted $R^2 = 0.973$). Population was the dominant correlate, with an elasticity of 1.099 (SE = 0.065, $P < 0.001$), meaning that a 1% increase in population corresponds to an estimated 1.1% rise in total e-waste generated—underscoring how demographic expansion directly scales electronic discards.

The scatter plot in Figure 3 (x = ln[Population, 2023]; y = ln[Total e-waste, million kg yr^{-1}] corroborates the regression estimates, showing a strong log–linear fit (elasticity ≈1.1, high adjusted R^2) with most countries clustering around population-predicted totals. Indonesia (19.45, 7.54) anchors the upper end, consistent with the near-proportional scaling of total e-waste with population. Thailand (18.09, 6.62) lies above the population-predicted line—despite a smaller population than the Philippines (18.56, 6.29)—reflecting Thailand's higher per-capita generation (10.5 kg $person^{-1}$ yr^{-1}). Positive deviations are most pronounced for Singapore (15.57, 4.80) and Brunei Darussalam (13.04, 2.20), whose totals exceed

Table 1. Regression Estimates of Structural Drivers of E-waste in Southeast Asia

Predictor	Coefficient (β)	Std. Error	t-value	*P*-value	Significance
(Intercept)	–21.769	1.870	–11.639	8.22e-05	***
log(Population)	1.099	0.065	16.961	1.30e-05	***
log(GDP per cap)	0.845	0.216	3.908	0.0113	**
Urbanization	–0.127	0.380	–0.333	0.7527	n.s.
Elec. Access	0.938	1.770	0.530	0.6189	n.s.
Adj. R²	0.973	—	—	—	—

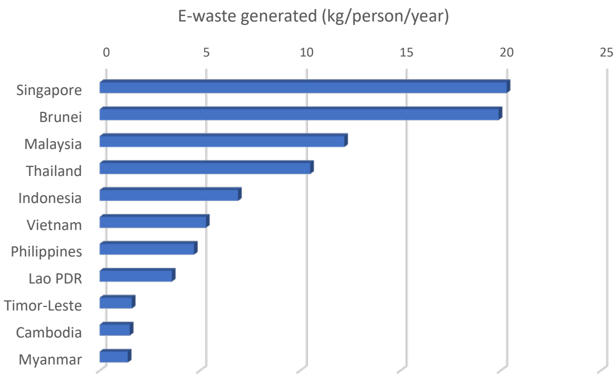

Figure 2. Per-capita E-waste (Annual Flows)

population-only expectations, consistent with affluence-driven replacement cycles. By contrast, Cambodia, Lao PDR, Myanmar, and Timor-Leste fall below the fitted line, in line with their low per-capita generation (≈1.5, 3.6, 1.4, and 1.6 kg person^{-1} yr^{-1}, respectively).

GDP per capita was also significant, with an elasticity of 0.845 (SE = 0.216, P = 0.011), which also shows a statistically significant positive relationship, indicating that a 1% rise in GDP per capita corresponds to an estimated 0.85% growth in total e-waste, underscoring the substantial influence of national income levels on electronic waste generation.

Figure 4—scatter with *x=In(GDP per capita, USD)* against *y=In(e-waste per capita, kg person^{-1}yr^{-1})*- substantiates the regression finding.

Affluent states such as Singapore (11.35, 3.01) and Brunei Darussalam (10.40, 2.99) lie well above the regional mean (~5–7 kg person^{-1} yr^{-1}), approaching 20 kg person^{-1} yr^{-1}. Malaysia (9.34, 2.50) and Thailand (8.88, 2.35) plot above other middle-income peers. At the same time, Vietnam, Indonesia, the Philippines, and Lao PDR cluster at modest levels, and Cambodia, Myanmar, and Timor-Leste remain lowest. These contrasts highlight income-driven consumption and replacement cycles as the structural mechanism behind cross-country disparities.

By contrast, as indicated in Table 1, urbanization (β = –0.127, SE = 0.380, P = 0.753) and electricity access (β = 0.938, SE = 1.770, P = 0.619) were not statistically significant once population and income effects were considered, suggesting that infrastructure-related factors play a secondary role.

Testing model robustness and estimate stability

Figure 5 presents the conceptual framework developed in this study, showing demographic and economic fundamentals as the structural drivers of e-waste in Southeast Asia. Solid arrows highlight significant effects, with population scaling total volumes and income shaping both total and per-capita generation. Dotted arrows mark non-significant paths—such as population to per-capita e-waste, urbanization, and electricity access—indicating these serve more as enabling conditions than independent drivers. As the analysis is based on cross-sectional official

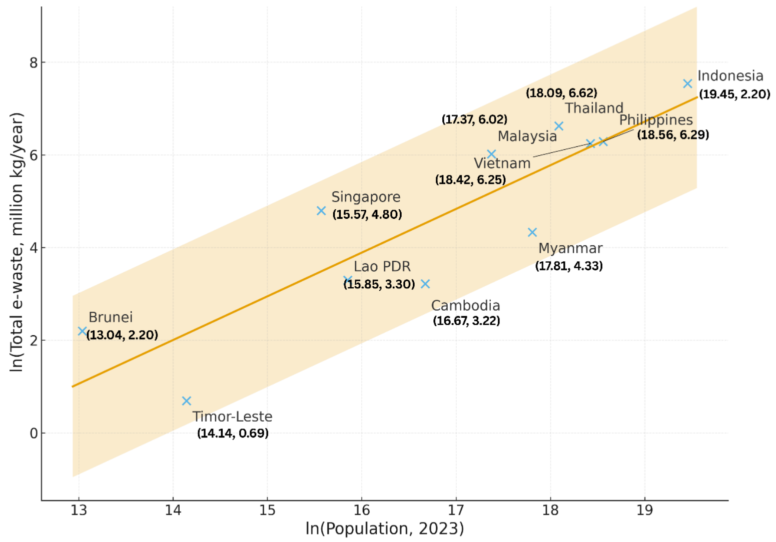

Figure 3. Scaling of Total E-Waste with Population in Southeast Asia

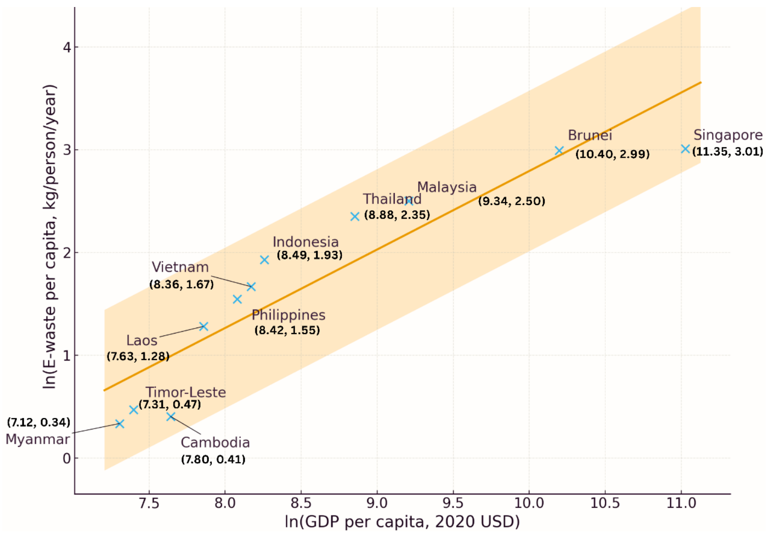

Figure 4. Income and E-Waste per Capita Generation

data and OLS log-linear regression, the relationships should be interpreted as descriptive associations rather than causal effects. Robustness checks (ϒ) further confirm the stability of these associations across specifications, underscoring their value as a baseline framework for future research.

Heteroskedasticity-robust inference and diagnostic results

Heteroskedasticity—non-constant variance of the error term—can bias standard errors and mislead inference. To assess this risk, variance behavior was examined using scale–location plots and a Breusch–Pagan screen (limited power at $n = 11$), with HC3 robust standard errors applied where variance instability was evident or plausible. HC3, designed for small samples and high-leverage cases, ensured valid inference.

As shown in Table 2, HC3-robust estimates (adjusted $R^2 = 0.973$ and 0.879) identify population and GDP per capita as significant drivers of total e-waste, while urbanization and electricity access remain insignificant. These results persist under variance correction, underscoring robustness. Residual diagnostics (Figure S5) confirmed model adequacy: residuals-versus-fitted showed linearity, Q–Q plots approximated normality, scale–location plots showed variance stability, and residuals versus leverage revealed no influential outliers.

Multicollinearity and drop-one diagnostics

Multicollinearity can inflate standard errors and destabilize estimates, so variance inflation factors (VIFs) were applied to assess model stability.

As shown in Table 3, all VIFs remain below conventional thresholds (≈5 noteworthy, ≈10 high), indicating no severe collinearity. GDP per capita (4.73) and urbanization (4.30) exhibit moderate overlap, modestly inflating their standard errors, but coefficients remain unbiased and the specification intact. Estimates for these predictors should therefore be interpreted with caution, with emphasis placed on effect sizes and confidence intervals rather than P-values.

Influence diagnostics

Influence tests confirm the stability of the results. As shown in Supplemental Tables S1a–S1b, no country exceeded leverage or Cook's distance thresholds, and studentized residuals remained within the acceptable bounds. Indonesia and Singapore had the highest leverage but were not influential. Leave-one-out (LOO) refits affirmed robustness: in the total e-waste model, population elasticity held at ≈1.09–1.13 and remained highly significant, GDP per capita stayed positive (≈0.62–0.79), and urbanization and electricity access were consistently non-significant. LOO stability checks (Table S2) showed only modest shifts—population elasticity varied within ± 3% (largest +7.3% excluding Brunei), while GDP per capita was most sensitive to Singapore (+29.5%) and Brunei (−18.6%) but remained positive throughout. No deletion altered the qualitative conclusions, confirming that no single country drives the results.

Discussion

The findings of this study align with extensive cross-national evidence. Widmer et al. (15) and Forti et al. (16) underscore prosperity as the decisive factor shaping global disparities, confirming that OECD economies generate per capita volumes three to four times higher than developing regions. In Latin America, Manomaivibool (17) found that institutional capacity, rather than urbanization, determined the effectiveness of extended producer responsibility (EPR).

Table 2. Log–linear OLS with HC3-Robust Standard Errors

Predictor	ln(Total e-waste)	ln(E-waste per capita)
Intercept	−20.870* (3.375)	−6.884 (3.716)
ln(Population)	1.104* (0.095)	0.098 (0.095)
ln(GDP per capita)	0.662* (0.264)	0.632 (0.264)
Urbanization rate	−0.115 (0.340)	−0.132 (0.354)
Urban electricity access	1.458 (3.500)	1.685 (3.975)

Table 3. Variance Inflation Factors Matrix

Predictor	VIF (ln Total e-waste)	VIF (ln Per-capita e-waste)
ln(Population)	1.21	1.21
ln(GDP per capita)	4.73	4.73
Urbanization (%)	4.30	4.30
Electricity access (%)	2.78	2.78

Note: VIF < 5 suggests no serious multicollinearity; values > 10 are generally problematic

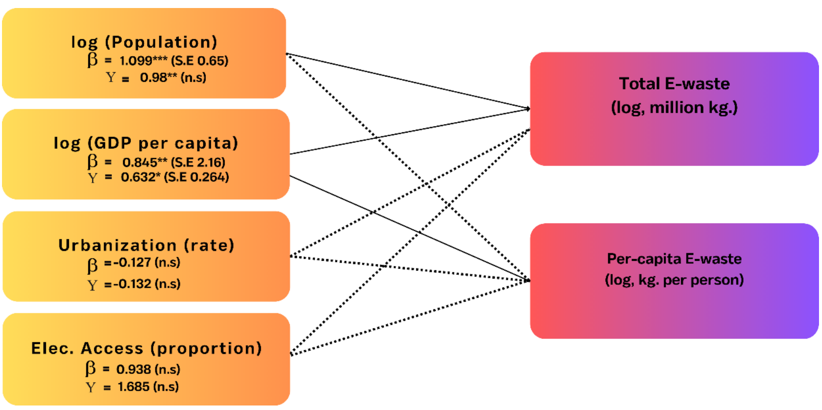

Figure 5. Conceptual Model of E-waste Dynamics in Southeast Asia

Similarly, in many African contexts, UN-Habitat reports that urbanization has occurred without proportional income growth or infrastructure gains, often resulting in low formal waste generation metrics—highlighting how urban expansion alone does not necessarily drive higher per-capita e-waste rates (18). Transitional economies such as China and India illustrate the dual logic: aggregate volumes scale with population size, while rising affluence drives per capita intensity (19,20).

This study also advances debates on urbanization's role in e-waste dynamics. Grossman and Krueger (21), in their seminal Environmental Kuznets Curve analysis, highlighted the empirical entanglement of income and urbanization, complicating causal attribution. Maddison (22) likewise found that urbanization often loses significance once GDP per capita is considered. The Southeast Asian evidence reinforces this view: in higher-income states such as Singapore, Malaysia, Thailand, and the Philippines, economic growth and urban expansion have moved in tandem, while in lower-income countries like Cambodia, urbanization has largely followed income gains. These patterns suggest that urbanization reflects prosperity rather than serving as an independent driver, challenging earlier studies that framed it as a standalone determinant (23,24).

In other words, the Southeast Asian case fits global regularities but adds nuance: infrastructure and urbanization enable uptake, yet affluence—and its mediation through institutions and informal practices—ultimately shapes waste intensity and management outcomes.

Comparative global evidence

The matrix in Table 4 situates Southeast Asia within broader global disparities. In 2022, the region generated 4.36 Mt of e-waste, averaging 6.4 kg per person per year—a level comparable to the Asian average but far below OECD benchmarks. By contrast, Europe produced 13.1 Mt (17.6 kg/person/year) and North America produced 8.0 Mt (21.2 kg/person/year), while Africa recorded only 2.5 kg/person/year.

These contrasts reflect global regularities: population size drives aggregate totals (e.g., China at 10.1 Mt/year), whereas affluence explains high per capita intensities regardless of geography (e.g., the United States at 21 kg/person/year). The SEA thus occupies a transitional position; its overall burden is already substantial, but per-capita trajectories are poised to rise further as incomes deepen.

Table 4. Comparative E-waste Generation

Region/Subregion	Total (Mt/year)	Per-capita (kg/person/year)	Documented Formal Collection Rate
Southeast Asia	4.362	6.4	0.0%
Europe	13.076	17.6	42.8%
Northern America	7.963	21.2	52.1%
Americas	14.427	14.1	30.0%
Asia	30.147	6.4	11.8%
Africa	3.551	2.5	0.7%
Oceania	0.707	16.1	41.4%
World	61.908	7.8	22.3%

Source: Global E-waste Monitor 2024, Annex 2 (Tables A2.2 & A2.3)

Collection rates and management disparities

Institutional gaps sharpen this contrast. Table 4 shows a documented collection rate of 0% in Southeast Asia, compared with 43% in Europe and 52% in North America. This figure does not imply an absence of collection but reflects the dominance of informal and undocumented flows. Informal systems, while efficient in recovering valuable fractions, remain outside regulatory oversight and rely on unsafe practices that externalize environmental and health costs (3,25). Laboratory evidence helps explain their persistence (26): A simple hydrometallurgical sequence achieved ~82% gold recovery at ~84% purity from CPU scrap without specialized extractants, though with toxic emissions and acidic effluents. Such reagent-accessible methods make acid-leaching economically attractive, even as they amplify environmental hazards.

The debate, therefore, is not whether e-waste is collected but how it is managed. In OECD economies, EPR, robust enforcement, and consumer engagement channel into auditable, safer systems. In Southeast Asia, by contrast, informal recovery dominates, turning structural pressures into unmanaged flows. The region's challenge is thus not material recovery per se, but redirecting value-driven yet hazardous practices into regulated and sustainable pathways.

Governance context and structural drivers

Global e-waste governance has coalesced around three pillars: EPR, product-side measures, and transboundary controls. EPR is central in many high- and middle-income settings, improving collection where enforcement is credible but remaining symbolic where institutional capacity is weak (16). Product-side measures—such as repairability standards and right-to-repair laws—aim to extend product lifetimes, while transboundary frameworks, notably the Basel Convention, restrict hazardous exports. However, enforcement is uneven, with Southeast Asia periodically absorbing diverted flows after China's bans.

Within this global context, the SEA region faces distinct constraints (4,27,28). Informal actors dominate collection and dismantling, extracting value efficiently but often at environmental and health costs. Collection logistics are shaped by the divide between dense urban centers and rural areas, while aspirational consumption and vibrant second-hand markets delay or bypass formal systems. Infrastructure maturity, including near-universal electrification, enables device uptake but does not independently explain waste generation. Instead, regression evidence confirms that population and income—rather than urbanization or electrification—are the decisive structural determinants. These dynamics highlight why the region cannot simply transplant OECD frameworks but must adapt governance to its demographic scale, income trajectories, and affluence-driven consumption.

Policy implications with country illustrations

Policy implications follow directly from these structural insights. Because aggregate volumes scale with population, collection targets should be calibrated to demographic size. As shown in Table 5, Indonesia, the Philippines, and Thailand dominate regional totals, much like China globally. For these states, population-based benchmarks—already used in OECD municipal waste planning (29)—would ensure proportional allocation of responsibilities and prevent small but affluent economies (e.g., Brunei, Singapore) from disproportionately shaping standards.

The income effect points to middle-income economies as priority sites for recycling system formalization. Vietnam and Malaysia, like South Korea in the 1990s (30,31), are undergoing rapid industrial transitions in which rising incomes translate into surging device turnover. Early investment in infrastructure, recycler certification, and consumer awareness is needed to prevent informal lock-in. The Philippines, while lower in per capita terms, faces a dual-track system (32): population-driven totals overwhelm rural infrastructure, highlighting the importance of scaling formal collection alongside governance reforms.

Affluent economies such as Singapore, Brunei, and Malaysia must anchor regional EPR frameworks. Singapore's 2021 EPR law demonstrates how producer responsibility can be institutionalized to finance collection and treatment (33), echoing European Union directives. Brunei has likewise moved early to institutionalize shared responsibility across producers, retailers, and regulators, indicating how small but wealthy states can prevent waste intensities from becoming unmanageable (34). Malaysia illustrates both progress and pitfalls: while there are legal frameworks, gaps in integrating informal collectors continue to undermine performance, pointing to the need for hybrid systems that align grassroots efficiency with formal oversight (35,36).

Embedding circular economy principles in national policy offers a pathway to decouple growth from waste. Measures that promote product longevity, repairability, and materials recovery can reduce environmental burdens while generating economic value (16,32). Malaysia's enforcement-linked strategy and Vietnam's evolving public–private models highlight promising localization options (4). Crucially, policies should integrate rather than prohibit informal actors through training, incentives, and safety standards. At the same time, consumer awareness campaigns foster responsible disposal, repair, and reuse as incomes and digital access expand.

ASEAN-level cooperation offers an additional lever. Platforms such as the ASEAN Working Group on Chemicals and Waste and the Circular Economy Stakeholders Forum can support harmonization, regional monitoring, and transboundary regulation. Progress toward a centralized regional mechanism with enforcement capacity would significantly strengthen Southeast Asia's collective response to the e-waste challenge (37).

Taken together, these differentiated pathways mirror global experiences—demographic scaling in the United States, early formalization in South Korea, and EPR-led transitions in the European Union—yet are uniquely combined in Southeast Asia. The region's mix of populous states, rapidly industrializing economies, and affluent city-states requires tailored approaches that align governance instruments with structural realities.

Two caveats merit attention. First, the analysis is based on 11 cross-sectional observations, which restricts statistical power and limits causal inference. The relationships identified through OLS regression should therefore be understood as descriptive associations, reflecting broad patterns rather than definitive causal effects, since unobserved dynamics and temporal variation could not be captured. Second, while regression diagnostics establish robustness, statistical precision remains constrained by measurement gaps in official data. Future research

Table 5. Comparative E-waste Governance in Southeast Asia

Country	Institutional Strengths	Key Gaps	Policy Priorities
Singapore	Strong EPR law (2021), integrated zero-waste strategy	High consumption-driven intensity	Consolidate EPR, expand repairability, and regional leadership
Brunei	Early adoption of the shared-responsibility framework	Small system, limited recycling infrastructure	Scale up collection, develop a formal recycler base
Malaysia	Longstanding e-waste laws, circular economy integration	Informal dominance, weak integration of grassroots actors	Hybrid systems linking informal and formal recycling
Indonesia	Ambitious national e-waste roadmap, green jobs framing	Infrastructure lag, low awareness, sheer scale of volumes	Invest in logistics, expand certified facilities
Philippines	Regulatory base (RA 9003), circular economy roadmaps	Enforcement gaps, rural infrastructure shortages	Strengthen enforcement, expand rural collection
Thailand	Strategic plans (2018, 2022)	No dedicated e-waste law, reliance on the informal sector	Enact law, formalize recycling networks
Vietnam	Hybrid public–private model, Decree 31/2020	Weak enforcement, low awareness	Strengthen compliance, expand formal collection
Cambodia	Environmental laws passed (2016, 2018)	Unsafe informal dominance, weak infrastructure	Bridge formal-informal divide, invest in facilities
Lao PDR	Initial producer-responsibility policy (2021)	Severe capacity constraints	Build regulatory and infrastructure capacity
Myanmar	Emerging EPR plan (2023)	Embryonic systems, import vulnerability	Institutionalize governance, curb unsafe practices
Timor-Leste	Early-stage engagement	Very low capacity, minimal systems	Establish baseline frameworks and monitoring

should incorporate time-series evidence, micro-level behavioral studies, and systematic evaluations of policy implementation. These extensions would sharpen causal inference and enhance the practical relevance of the structural insights for governance design.

Conclusion

This study establishes a regional baseline for understanding the structural determinants of e-waste in Southeast Asia. The evidence confirms that population size drives aggregate volumes, while rising affluence drives per-capita intensity; urbanization and electrification are derivative markers rather than independent factors. These insights provide a foundation for differentiated policy: demographic scaling of collection, early formalization in middle-income economies, and EPR adoption in affluent states. By aligning global frameworks with regional realities, Southeast Asia can reduce reliance on unsafe informal practices and build pathways toward a circular economy.

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Competing Interests

The author declares no conflict of interest.

Ethical Approval

This investigation was conducted with unwavering commitment to ethical research standards, implementing predefined protocols that ensured methodological transparency, inherent reproducibility, and a systematic minimization of bias.

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Supplementary Files

Supplementary file 1 contains Figures S1-S5 and Tables S1 and S2.

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