Mathematical Modelling of Industrial Waste Flow in Closed-Loop Manufacturing Systems

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Abstract: ***Industrial waste management in India faces significant challenges despite regulatory frameworks and infrastructure investments, with substantial discrepancies between reported recycling rates and actual material recovery. This study employs a dual-stream material flow model to quantify waste generation, recycling, and disposal pathways across Gujarat, Maharashtra, and Tamil Nadu during 2019-2025, explicitly distinguishing between formal institutional mechanisms and informal recovery networks. Using Central Pollution Control Board data supplemented by secondary sources on informal sector activities, the analysis reveals that informal recycling contributes 76.1% of hazardous waste recovery and 56.2% of solid waste recovery despite operating largely unrecognized in official statistics. Correlation analysis demonstrates strong negative relationships between recycling rates and landfilled waste (r = -0.907 overall), with Gujarat and Maharashtra achieving near-perfect inverse correlations while Tamil Nadu exhibits greater variability. Spatial analysis positions these states among India's top waste generators, with Maharashtra producing the highest volumes (22,945-24,122 TPD), yet Gujarat demonstrates exceptional recycling efficiency (93.2-98.6%), indicating that institutional capacity outweighs absolute waste volumes in determining success. The dual-stream model reveals gaps of 15.8-40.1 percentage points between theoretical recycling potential and observed outcomes, quantifying the costs of exclusionary governance. Sensitivity analysis confirms that marginal improvements in informal sector integration yield significantly higher returns than equivalent formal infrastructure investments. These findings challenge assumptions that India's waste management inadequacy stems from technological deficiencies, instead highlighting fragmented governance, lack of formal recognition for informal workers, and weak institutional linkages as primary constraints. The study recommends systemic reforms including formal recognition of informal contributions, hybrid integration models, enhanced data transparency, and institutional coordination to achieve effective, inclusive, and circular waste management.***

Keywords: Industrial waste management, informal recycling, dual-stream material flow model, waste governance, circular economy, India

1. Introduction

India's rapid industrialisation has positioned the nation as one of the world's fastest-growing economies, yet this economic transformation has generated unprecedented environmental challenges, particularly in industrial waste management. The scale of this challenge is substantial as India generates approximately 7.46 million tonnes of hazardous industrial waste annually from over 40,000 industrial facilities, alongside an estimated 160,000 tonnes of municipal solid waste daily (CPCB, 2023; Sharma & Jain, 2020). This enormous volume of waste, encompassing chemical residues, metal sludges, hazardous effluents, and solid industrial by-products, poses severe environmental and public health risks when improperly managed (Tawo et al., 2025; Salaria et al., 2024). Despite regulatory frameworks such as the Hazardous and Other Wastes (Management and Transboundary Movement) Rules of 2016, significant gaps persist in implementation and enforcement across state jurisdictions (CPCB, 2023; Rani & Srivastav., 2022; Thapa et al., 2023).

Preserving natural resources and minimizing ecological footprints are critical imperatives for ensuring long-term environmental sustainability and intergenerational equity (Panday et al., 2026; Agarwal et al., 2025; Singh et al., 2025; Vishvendra et al., 2024). A fundamental challenge in addressing India's waste crisis lies in the structural disconnect between formal regulatory systems and ground realities. Official waste inventories maintained by the Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs) capture only those waste streams that enter registered treatment, storage, and disposal facilities. However, a substantial proportion of India's recyclable waste, estimated at 60-70 percent, is intercepted and processed by an extensive informal recycling sector comprising waste pickers, kabadiwalas (scrap dealers), and small-scale recyclers operating outside formal regulatory frameworks (Wilson et al., 2015; Aparcana, 2017). This informal sector, employing approximately 4 million people across the country, performs critical material recovery functions that remain largely invisible in official statistics (Sengupta et al., 2023; Kala & Bolia, 2022). The resulting data gap creates a fundamentally incomplete picture of national waste flows, undermining the effectiveness of policy interventions and infrastructure planning.

Existing research on India's industrial waste management has predominantly focused on isolated aspects of the system. Early studies by Kumar et al. (2017) and Mor et al. (2006) concentrated on hazardous waste prediction and risk assessment using linear regression and time-series models, relying exclusively on CPCB-registered data. These approaches, while valuable for forecasting trends within the formal sector, fail to account for the substantial material recovery occurring through informal channels before waste enters official processing streams. Sectoral studies by de Oliveira et al. (2020) utilized discrete event simulation to analyze treatment efficiency in small-scale industrial clusters, yet did not consider inter-sectoral material transfers or the role of informal recycling networks. Similarly, econometric analyses by Kala & Bolia, (2024) examined hazardous waste inventories without incorporating mass conservation principles or feedback loops from recycling activities. Notably absent from this body of literature is an integrated modelling framework that encompasses the complete waste pathway, from industrial generation through both formal and informal recovery channels to final disposal or reuse.

In contrast, international research on waste management offers more sophisticated methodological approaches, particularly in the domains of material flow analysis (MFA), circular economy modelling, and industrial ecology. Studies conducted in the European Union and East Asia demonstrate that combining MFA techniques with system dynamics or statistical modelling produces more accurate characterizations of waste streams and enables significant improvements in resource recovery rates (Ghisellini et al., 2016; Islam and Huda, 2019; Haupt and Hellweg, 2019). Research from Japan and South Korea reveals that formal integration of informal or small-scale waste recyclers into national waste management models can enhance circular economy recovery rates by 25-40 percent, underscoring the critical importance of accounting for informal waste streams in developing economies (Park and Chertow, 2014; Geissdoerfer et al., 2017). More recent work specifically focused on India's informal recycling systems has documented that informal actors frequently achieve recovery efficiencies exceeding those of formal facilities, particularly for high-value materials such as metals, plastics, and electronic waste (Shankar et al., 2023; Kumar and Agrawal, 2020). Despite these insights, no comprehensive mathematical framework has yet integrated formal CPCB inventory data, informal sector contributions, and material flow principles into a unified systems model of India's industrial waste dynamics.

The originality of this research lies in its development of a dual-stream material flow model that explicitly represents India's bifurcated waste management system as a partially closed-loop process. Unlike previous linear models that conceptualize waste flow as a unidirectional path from generation to disposal, this framework recognizes and quantifies the cyclic processes introduced by both formal and informal recycling activities. The model incorporates regression-derived flow coefficients that enable dynamic adjustment of system parameters in response to policy changes, economic shifts, or variations in recovery infrastructure. This approach allows for scenario analysis and policy evaluation that were not possible with previous modelling methodologies. Furthermore, the research enhances accessibility and stakeholder engagement through the use of GIS, bar graphs, and trend visualizations that communicate complex material flows and system inefficiencies to non-technical audiences, including policymakers, industry representatives, and civil society organizations.

The practical applications of this research framework are multifaceted and address critical gaps in India's environmental governance infrastructure. At the national level, regulatory bodies such as the CPCB and the Ministry of Environment, Forest and Climate Change (MoEFCC) can utilize the model to construct comprehensive annual inventories that capture both formal and informal waste flows, thereby improving the accuracy of national reporting and enabling evidence-based policy formulation. The model's capacity to identify data gaps and system leakages provides a foundation for targeted interventions in waste tracking, collection infrastructure, and recycling capacity development. For industrial stakeholders operating under Extended Producer Responsibility (EPR) mandates, the framework offers predictive capabilities to identify optimal recovery opportunities and assess the feasibility of closed-loop manufacturing initiatives. State and municipal planning authorities can leverage the model's spatial outputs to identify geographic concentration of industrial waste generation, supporting optimization of treatment facility locations and transportation logistics. At the international level, the methodological framework is transferable to other developing economies characterized by substantial informal recycling sectors, potentially informing waste management reform efforts across South Asia, Sub-Saharan Africa, and Latin America.

This study pursues three primary research objectives. First, it aims to integrate fragmented datasets spanning the decade from 2013 to 2023, combining formal CPCB inventories with estimates of informal sector activity to construct a unified time-series of industrial waste generation, recovery, and disposal. Second, employing regression analysis, the research identifies key drivers of waste generation and recovery efficiency, examining relationships between industrial production patterns, regulatory enforcement, and material flow dynamics. Third, using mass balance principles, the study develops and calibrates a dual-stream material flow model that quantifies transformation and recovery processes across both formal and informal pathways, with explicit treatment of capture rates, processing efficiencies, and system losses. By incorporating informal sector contributions that have historically been excluded from official analyses, this research provides a more complete and empirically grounded representation of India's industrial waste system.

Conceptually, this research contributes to a fundamental reframing of waste as a resource within interconnected industrial ecosystems, aligning with circular economy principles that emphasize material cycling, value retention, and system regeneration (MacArthur, 2015; Homrich et al., 2018). The originality of the modelling approach lies not only in its technical architecture but also in its explicit recognition of the invisible efficiencies embedded within India's informal recycling networks. Rather than treating informal actors as operating outside the boundaries of legitimate waste management systems, this framework positions them as essential drivers of material recovery and circular economy transition. By challenging prevailing policy narratives that frame informal recycling as marginal or problematic, the research opens new pathways for inclusive governance models that build upon existing informal capacity rather than seeking to replace it entirely. This perspective shift has significant implications for India's ability to achieve national sustainability targets, reduce dependence on virgin material imports, and create employment opportunities within formalized green economy sectors while preserving the livelihood security of existing informal workers.

This study addresses a critical gap in India's waste management knowledge infrastructure by developing an integrated analytical framework that captures the full complexity of industrial waste flows across formal and informal domains. Through rigorous data integration, statistical analysis, and systems modelling, the research provides evidence-based foundations for policy reform, infrastructure investment, and institutional coordination that can accelerate India's transition toward a more circular, inclusive, and sustainable industrial economy. The following sections detail the study area characteristics, methodological approach, empirical findings, and policy recommendations derived from this comprehensive analysis of India's industrial waste management system.

2. Study Area

India was chosen as the case area because of its level of industrial activity, diversity of industrial sectors, and presence of both formal and informal solid waste management practices. With one of the most rapidly expanding industrial economies in the world, India produces a broad range of industrial wastes, which include hazardous industrial wastes, solid industrial wastes, and recyclables. Regions in India also experience varying amounts of industrial wastes, which range depending on levels of industrialization, urbanization, infrastructure, and effectiveness of regulations. Analysis of industrial waste at a macro-level, therefore, requires a geographical perspective. Against this national scenario, a certain set of states has been chosen for a state-level analysis: Gujarat, Maharashtra, and Tamil Nadu. These account for a substantial portion of Indian industrial production and share different set of properties for waste management.

Gujarat is a significant chemical production, petrochemicals, pharmaceuticals, and metal processing center for India, with many industrial estates and special economic zones, thereby intensifying hazard waste generation even with a substantial waste recycling gap, thereby marking a critical case for studying systemic inefficiencies. Maharashtra, the most industrialized State in terms of economic activity, integrates large-scale industrial activity with congested urban settlements, such as Mumbai, Pune, among others. Maharashtra produces the highest amounts of solid as well as industrial waste, thanks to its diverse industrial activity, such as the manufacture of automobiles, electronics, textiles, food processing, among others. Maharashtra shows the highest recycling potential compared to other States, but the unorganized waste recycling sector is deeply ingrained, especially within the urban, peri-urban areas. The case of Tamil Nadu is representative of a product-manufacturing economy and has a thriving textile industry, leather industry, automobile industry, and electronics industry. The industrial activities are mainly around the city of Chennai, Coimbatore, and Tiruppur. There is a moderate level of recycling performance when it comes to the states of Gujarat and Maharashtra; however, the major share of recycling is done by the unorganized sector.

These three states together offer a representative cross-section of Indian industrial waste. Including these three states allows for a comparative assessment of waste creation, recycling rates, and the participation of the unorganized sector. In integrating an assessment at the state level and within a nationwide spatial framework, this research seeks to link local dynamics and broader systemic patterns pertaining to waste.

3. Methods and Data

3.1 Data Sources and Study Design

This study employs a quantitative, systems-oriented methodology to analyze industrial waste generation and recycling across India, with particular emphasis on distinguishing formal and informal waste management pathways. The analysis spans 2019-2025, focusing on three states, Gujarat, Maharashtra, and Tamil Nadu, selected based on their substantial waste generation volumes, diverse industrial profiles, and varying recycling performance trajectories. Data were primarily sourced from the Central Pollution Control Board (CPCB) annual waste inventories, which provide state-level statistics on waste generation, collection, treatment, and disposal for both hazardous and solid waste streams. Supplementary data were obtained from State Pollution Control Boards (SPCBs) and data.gov.in to ensure comprehensiveness and validate consistency across reporting periods.

A critical limitation of official datasets is their systematic exclusion of informal recycling activities. To address this gap, the study integrates secondary estimates from academic literature, NGO reports, and policy studies documenting India's informal recycling economy. These sources quantify the contributions of informal actors, including scrap dealers (kabadiwalas), waste pickers, and small-scale recyclers, who capture and process recyclables before materials enter formal waste management systems. Rather than treating informal contributions as exogenous adjustments, these estimates are structurally embedded within the analytical framework through capture rate and efficiency parameters.

3.2 Dual-Stream Material Flow Model

The core analytical tool developed in this study is a dual-stream material flow model that conceptualizes industrial waste management as a bifurcated system comprising formal and informal pathways operating in parallel. Total industrial waste generation (W_{total}) is treated as a conserved quantity partitioned between waste entering informal recovery networks ($W_{informal}$) and waste directed to formal, CPCB-registered facilities (W_{formal}). This formulation maintains mass balance across the system while enabling differential assessment of recycling performance across sectors.

The model is governed by two fundamental equations:
Equation 1: Mass Balance

$$W_{total} = W_{informal} + W_{formal}.$$

This equation partitions total waste generation based on the informal capture rate (α), representing the proportion of waste intercepted by informal networks before formal processing. The complementary fraction (1-α) enters the formal stream directly.

Equation 2: Total Recycling

$$R_{total} = (\eta_{informal} \times \alpha \times W_{total}) + (\eta_{formal} \times (1-\alpha) \times W_{total})$$

where, W_{total}: Total waste generated (MT/year), $W_{informal}$: Waste handled by informal sector (scrap dealers, waste pickers), W_{formal}: Waste entering formal, government-registered facilities, R_total: Total waste recycled (combined formal and informal contributions), α (alpha): Informal sector capture rate ($0 \leq \alpha \leq 1$), Hazardous waste: $\alpha = 0.20$ (20%), Solid waste: $\alpha = 0.45$ (45%), η_informal: Informal sector recycling efficiency (0.75-0.85, or 75-85%), η_formal: Formal sector recycling efficiency (0.40-0.60, or 40-60%), (1-α): Fraction entering formal sector directly.

Parameter values for capture rates and recycling efficiencies were derived from empirical studies documenting informal and formal recycling performance in India and comparable developing economies. Hazardous waste parameters assume lower informal capture rates ($\alpha = 0.20$) due to regulatory controls and safety concerns, while solid waste parameters reflect higher informal penetration ($\alpha = 0.45$) given the extensive networks for recovering valuable materials like metals, plastics, and textiles.

3.3 Model Calibration and Validation

Initial model runs using literature-based efficiency parameters produced theoretical recycling rates substantially exceeding observed CPCB data, particularly for hazardous waste streams. For instance, Gujarat's theoretical hazardous waste recycling potential reached 47.0% (1,548,107 MT), while observed recycling was only 6.9% (227,275 MT). This discrepancy quantifies the gap between system capacity and actual performance, attributable to institutional inefficiencies, regulatory bottlenecks, and inadequate waste routing infrastructure rather than model inadequacy.

To reconcile theoretical predictions with empirical reality, calibration was performed by constraining total recycled waste (R_total) to observed CPCB values while preserving the ratio of informal-to-formal contributions determined by the uncalibrated model. This approach maintains structural insights regarding sectoral dominance without arbitrarily reducing efficiency parameters. Calibrated results reveal that informal recycling accounts for approximately 70% of hazardous waste recovery and 52.8-69.0% of solid waste recovery across the three states, despite operating largely outside formal recognition.

3.4 Spatial Analysis and Visualization

State-level waste generation data were analysed to produce spatial distribution maps identifying regional concentrations of waste production across India. Heat maps visualized waste generation intensity ranging from 14,433 to 81,342 tonnes per day (TPD), highlighting correlations with urbanization patterns and industrial clustering. Comparative bar charts positioned the three study states within the national context, demonstrating their significance as major waste generators requiring priority interventions.

3.5 Statistical Analysis

Correlation analysis was conducted to quantify relationships between waste management parameters including generation, collection, treatment, landfilling, and recycling rates. Pearson correlation coefficients were calculated for overall datasets and disaggregated by state to identify divergent patterns and performance trajectories. Sensitivity analysis tested model robustness across varying parameter assumptions, confirming that total recycling outcomes exhibit high elasticity with respect to informal capture rates and efficiency levels.

The mathematical model implemented in Python using libraries including Pandas, NumPy, Matplotlib, and Seaborn. Complete Python code for model implementation, calibration procedures, and visualization generation is provided in the Supplementary Material (Section 1) accompanying this publication.

4. Results and Discussion

4.1 Waste distribution pattern in India

The spatial analysis of solid waste generation across India reveals significant geographical heterogeneity, with waste generation patterns closely aligned with population density, urbanization levels, and economic development (Figure 1). The heat map (Figure 1a) demonstrates that solid waste generation ranges from 14,433 TPD to 81,342 TPD across different states and union territories, with the highest concentrations observed in western, southern, and northern regions of the country. This spatial variation reflects the uneven distribution of urban centers and industrial hubs across India's landscape. Maharashtra emerges as the largest waste generator among the three study states, producing between 22,945 TPD and 24,122 TPD during the study period, which correlates with its status as India's second-most populous state and its high degree of urbanization, particularly in metropolitan areas like Mumbai, Pune, and Nagpur. The state's extensive industrial base, coupled with a rapidly growing service sector, contributes to elevated per capita waste generation rates. Similarly, Tamil Nadu, with waste generation ranging from 14,228 TPD to 15,748 TPD, ranks among the top waste-producing states, reflecting the industrial and urban concentration in Chennai, Coimbatore, and surrounding districts, which serve as major manufacturing and textile production centers.

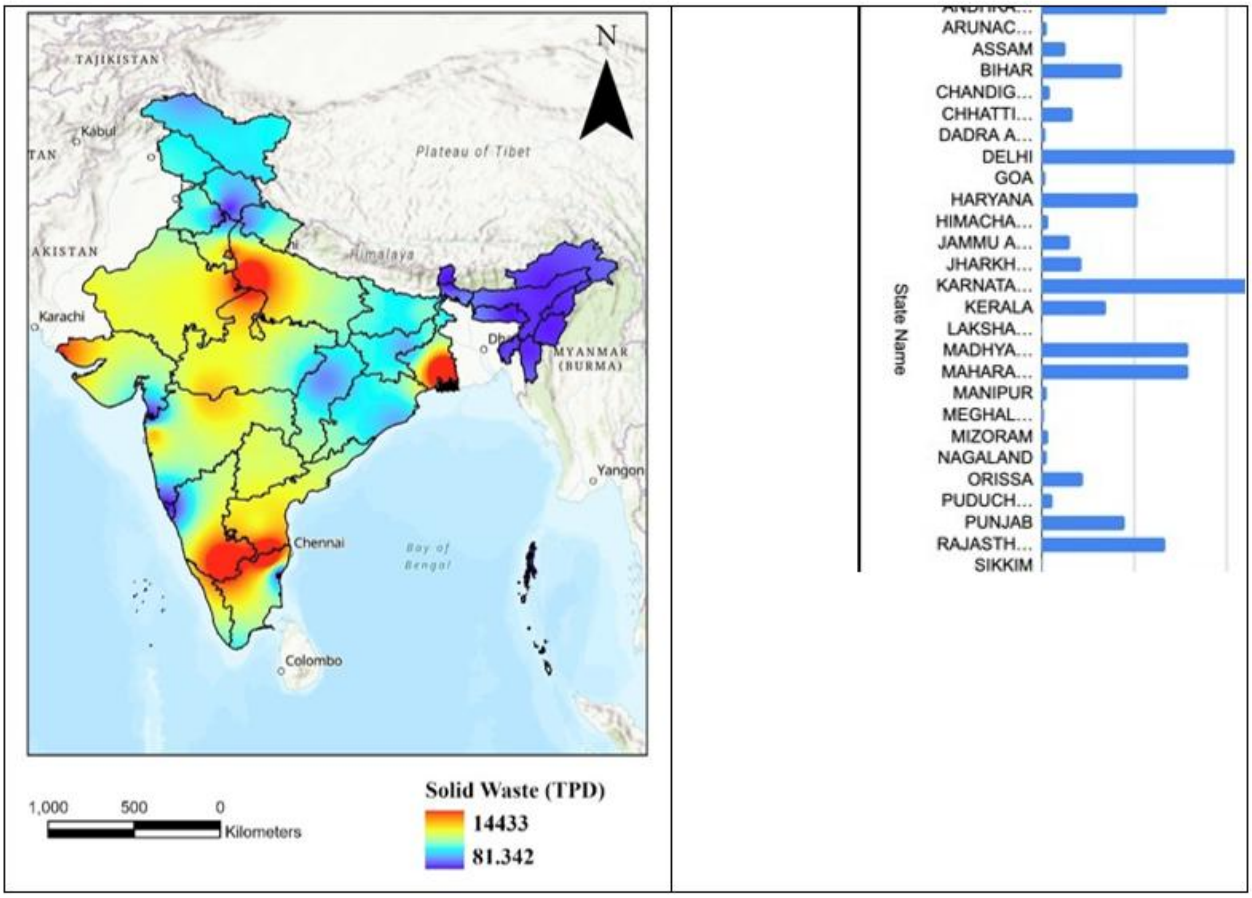

Figure 1: Geographical distribution of solid waste generation in India: (a) Spatial heat map showing regional variations, and (b) State-wise quantitative comparison of waste generation (in Tonnes Per Day)

Gujarat's relatively moderate waste generation (9,776 TPD to 10,828 TPD) compared to Maharashtra and Tamil Nadu belies its exceptional recycling efficiency, suggesting that effective waste management is not solely dependent on the absolute quantum of waste but rather on the robustness of treatment infrastructure, policy implementation, and public participation in waste segregation initiatives. The state's lower waste generation figures, despite substantial industrial activity in cities like Ahmedabad, Surat, and Vadodara, may also indicate more effective waste minimization strategies at the source and better enforcement of plastic waste management rules. This finding challenges the conventional assumption that higher economic development necessarily correlates with proportionally higher waste generation, instead highlighting the role of regulatory frameworks and civic awareness in moderating waste production. The spatial distribution pattern also reveals interesting insights about coastal states, where both Maharashtra and Tamil Nadu show elevated waste generation, possibly attributable to higher population densities in coastal urban centers and the presence of port cities that facilitate trade and industrial activities.

The comparative bar chart analysis (Figure 1b) provides a comprehensive national perspective, positioning the three study states within the broader context of India's solid waste management landscape and revealing the magnitude of the national waste management challenge. Among the top waste-generating states, Uttar Pradesh, Tripura, and West Bengal exhibit the highest waste generation (approximately 14,000-14,500 TPD each), followed closely by Maharashtra and Tamil Nadu. Uttar Pradesh's position as the highest waste generator is attributable to its status as India's most populous state, with over 200 million inhabitants distributed across numerous urban centers including Lucknow, Kanpur, Varanasi, and Agra. This ranking underscores the challenges faced by heavily populated and rapidly urbanizing states in managing increasing waste volumes, particularly when infrastructure development lags behind urban expansion. The data reveals a clear disparity between high-generating states and smaller states or union territories, where waste generation remains below 2,000 TPD. States such as Meghalaya, Nagaland, and Mizoram, despite their geographical size, generate substantially less waste due to lower population densities, limited urban development, and traditional lifestyles that typically involve lower consumption of packaged goods and disposable products.

This spatial variation highlights the need for differentiated waste management strategies that account for state-specific demographic, economic, and infrastructural contexts rather than adopting a uniform national approach. The northeastern states, for instance, may benefit from decentralized, community-based waste management systems that align with their dispersed settlement patterns, while high-generating states require large-scale, technologically advanced processing facilities. The middle-tier waste generators, including states like Karnataka, Kerala, Madhya Pradesh, and Rajasthan (generating between 3,000-12,000 TPD), represent an intermediate category where moderate urbanization coexists with significant rural populations, necessitating hybrid waste management models that integrate both urban and rural waste collection and processing systems.

The position of waste generation patterns with recycling performance metrics from the three focus states reveals critical insights into waste management effectiveness and the disconnect between waste production and waste processing efficiency. While Maharashtra and Tamil Nadu are among the highest waste generators nationally, their divergent recycling trajectories, Maharashtra achieving 93.3% and Tamil Nadu managing 64.4% by 2023-24 demonstrate that high waste generation does not inherently preclude efficient resource recovery. Gujarat's position as a moderate waste generator but top recycling performer (93.2-98.6%) further reinforces that institutional capacity, technological adoption, regulatory enforcement, and public-private partnerships are more determinative of recycling success than the absolute volume of waste. The spatial clustering of high waste-generating states in economically developed regions suggests that rapid urbanization and economic growth, while contributing to waste generation, can also provide the financial and institutional resources necessary for developing sophisticated waste management systems, including mechanized collection, automated sorting facilities, and waste-to-energy plants.

However, the persistent challenges in states like Tamil Nadu, despite adequate resource availability, indicate that financial capacity alone is insufficient without consistent policy implementation, inter-departmental coordination, and active public participation in waste segregation and recycling initiatives. The geographical analysis also emphasizes the importance of regional cooperation and knowledge transfer mechanisms, whereby high-performing states like Gujarat and Maharashtra can serve as models for other states struggling with waste management challenges. Furthermore, the spatial patterns suggest that waste management policies must be sensitive to regional variations in waste composition, which differs significantly between agricultural states, industrial states, and service-sector-dominated economies.

4.2 Correlation Assessment of Waste Management Indicators

The correlation analysis shown in Figure 2, reveals significant relationships between various waste management parameters across Gujarat, Maharashtra, and Tamil Nadu during 2019-2024. The overall analysis demonstrates a strong negative correlation (-0.907) between recycling rate and waste landfilled, indicating that states achieving higher recycling rates consistently reduce their dependence on landfilling. This inverse relationship is particularly pronounced in Gujarat (-0.999) and Maharashtra (-0.998), where near-perfect negative correlations suggest highly effective waste diversion strategies. Conversely, a moderate positive correlation (0.595) exists between waste treated and recycling rate at the aggregate level, emphasizing that increased treatment infrastructure directly contributes to improved recycling performance. The near-perfect correlation (0.999) between waste generated and waste collected across all states indicates comprehensive collection systems, though the efficiency of subsequent treatment varies considerably.

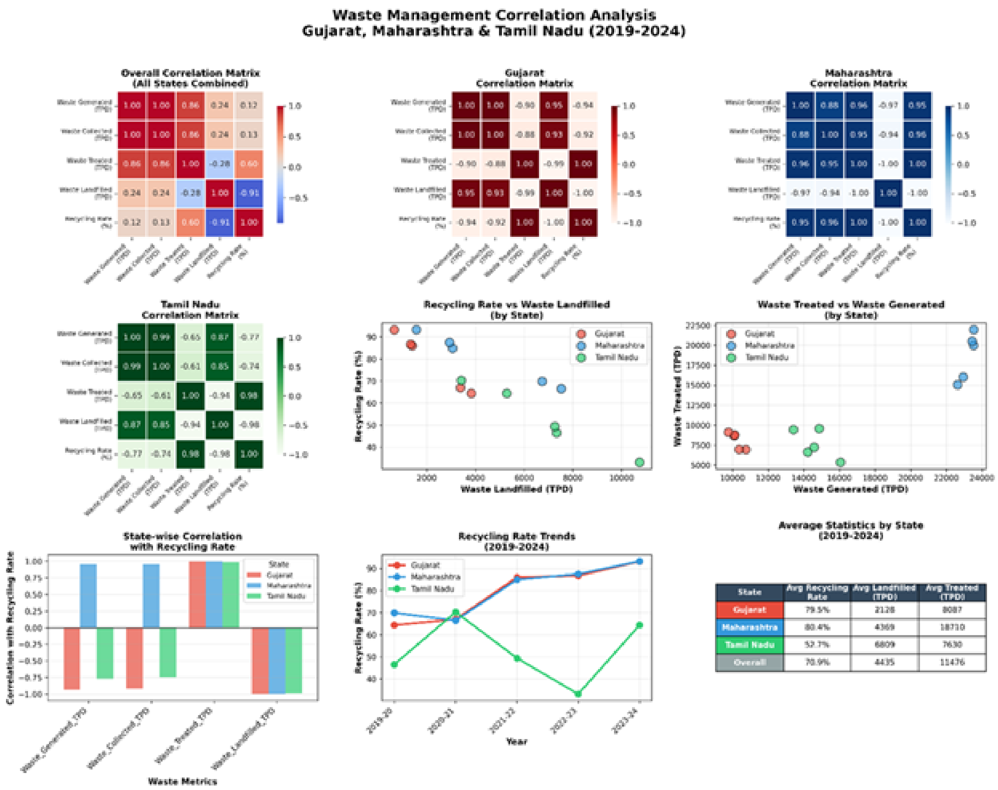

Figure 2: Multi-dimensional correlation analysis of waste management performance across three Indian states (2019-2024). Top row: Correlation matrices for all states combined, Gujarat, Maharashtra, and Tamil Nadu. Middle row: Scatter plots depicting recycling rate versus waste landfilled (by state) and waste treated versus waste generated (by state). Bottom row: State-wise correlation bar charts with recycling rate, temporal trends showing recycling rate evolution, and average statistics table summarizing performance metrics.

State-specific patterns reveal distinct waste management trajectories. Maharashtra demonstrates the strongest positive correlation (1.000) between waste treatment and recycling rate, reflecting its systematic approach to processing collected waste into recyclable materials. The state's recycling rate improved from 69.9% in 2019-20 to 93.3% in 2023-24, accompanied by a dramatic reduction in landfilled waste from 6,742 TPD to 1,578 TPD. Gujarat exhibits similar efficiency with a correlation of 0.995 between treatment and recycling, achieving the highest recycling rate of 93.2% by 2023-24 while reducing landfilled waste to just 669 TPD. In contrast, Tamil Nadu shows greater variability with weaker correlations, particularly a negative relationship (-0.769) between waste generated and recycling rate, suggesting infrastructural challenges in scaling treatment capacity proportionate to waste generation, which increased from 14,228 TPD to 14,859 TPD over the study period.

Year-wise waste generation, collection, treatment, landfilling, and recycling rates for Gujarat, Maharashtra, and Tamil Nadu (2019-2025) is summarised in Table 1. The temporal analysis further highlights divergent development patterns among states. While Gujarat and Maharashtra demonstrate consistent upward trends in recycling rates with minimal fluctuation, Tamil Nadu's performance shows considerable volatility, with recycling rates ranging from 33.1% to 70.3% across different years. This variability, coupled with the highest average landfilled waste (7,014 TPD) among the three states, indicates persistent gaps in treatment infrastructure and operational consistency. The strong negative correlations observed in Gujarat and Maharashtra between landfilling and recycling underscore the effectiveness of their integrated waste management strategies, which prioritize treatment and resource recovery over disposal. These findings suggest that sustained improvements in recycling performance require not only adequate treatment capacity but also consistent operational protocols and policy enforcement mechanisms.

Table 1: Waste management statistics across Gujarat, Maharashtra, and Tamil Nadu (2019-2025)

State	Year	Waste Generated (TPD)	Waste Collected (TPD)	Waste Treated/ Processed (TPD)	Waste Landfilled (TPD)	Recycling Rate (%)
Gujarat	2019-20	10755	10755	6924	3831	64.4
Maharashtra		22945.256	22779.31	16037.26	6742.05	69.9
Tamil Nadu		14228	13955	6620	7335	46.5
Gujarat	2020-21	10373.79	10332	6946	3386	67
Maharashtra		22632.71	22584.4	15056.1	7528.3	66.5
Tamil Nadu		13422	12844	9430.35	3413.65	70.3
Gujarat	2021-22	10095	10095	8682	1413	86
Maharashtra		23531	23044	19980	3064	84.9
Tamil Nadu		14586	14471	7206	7265	49.4
Gujarat	2022-23	10116	10116	8775	1341	86.7
Maharashtra		23448.46	23448.46	20515	2933.46	87.5
Tamil Nadu		16066.39	16066.39	5325	10741.39	33.1
Gujarat	2023-24	9776	9776	9107	669	93.2
Maharashtra		23539	23539	21961	1578	93.3
Tamil Nadu		14859	14859	9570	5289	64.4
Gujarat	2024-25	10828	10828	10673	155	98.6
Maharashtra		24122	24122	22520	1602	93.4
Tamil Nadu		15748	15748	10105	5643	64.2

4.3 Mathematical Model Outputs and Dual-Stream Waste Flow Analysis

A dual-stream modelling approach, specifically designed within the framework of this study, enables the quantitative assessment of waste generation, capture, recycling, and disposal processes across both formal and informal sectors in India's waste management system. By explicitly accounting for formal institutional mechanisms and informal recovery networks as parallel yet interdependent streams, this modelling framework addresses a critical gap in traditional waste inventories that fail to capture the full spectrum of material flows. Model results are summarised in Table 2.

Table 2: Dual-stream waste flow model results showing theoretical predictions, observed reality, and calibrated outputs for hazardous and solid waste management across three states

State	Hazardous Waste Analysis	Solid Waste Analysis
Gujarat	Parameters: α=0.2, η_informal=0.75, η_formal=0.4 EQUATION 1: W_total = W_informal + W_formal 3,293,844 = 658,769 + 2,635,075 ✓ Equation 1 verified EQUATION 2: R_total = (η_informal × α × W_total) + (η_formal × (1-α) × W_total)	Parameters: α=0.45, η_informal=0.85, η_formal=0.6 EQUATION 1: W_total = W_informal + W_formal 3,798,894 = 1,709,502 + 2,089,392 ✓ Equation 1 verified EQUATION 2: R_total = (η_informal × α × W_total) + (η_formal × (1-α) × W_total) R_total = (0.85 × 0.45 × 3,798,894) + (0.6 × 0.55 ×

	R_total = (0.75 × 0.2 × 3,293,844) + (0.4 × 0.80 × 3,293,844) R_total = 494,077 + 1,054,030 R_total = 1,548,107 MT Model Prediction: 1,548,107 MT (47.0%) Observed Reality: 227,275 MT (6.9%) ⚠ Model needs calibration. Using observed value for analysis. FINAL RESULTS: • Total Waste (W_total): 3,293,844 MT • Informal Sector (W_informal): 658,769 MT • Formal Sector (W_formal): 2,635,075 MT • Total Recycled (R_total): 227,275 MT • Informal Recycling (R_informal): 159,093 MT • Formal Recycling (R_formal): 68,183 MT • Total Landfilled: 3,066,569 MT • Informal Contribution: 70.0% • Formal Contribution: 30.0%	3,798,894) R_total = 1,453,077 + 1,253,635 R_total = 2,706,712 MT Model Prediction: 2,706,712 MT (71.2%) Observed Reality: 2,752,166 MT (72.4%) ⚠ Model needs calibration. Using observed value for analysis. FINAL RESULTS: • Total Waste (W_total): 3,798,894 MT • Informal Sector (W_informal): 1,709,502 MT • Formal Sector (W_formal): 2,089,392 MT • Total Recycled (R_total): 2,752,166 MT • Informal Recycling (R_informal): 1,453,077 MT • Formal Recycling (R_formal): 1,299,089 MT • Total Landfilled: 1,046,728 MT • Informal Contribution: 52.8% • Formal Contribution: 47.2%
Maharashtra:	Parameters: α=0.2, η_informal=0.75, η_formal=0.4 EQUATION 1: W_total = W_informal + W_formal 990,051 = 198,010 + 792,041 ✓ Equation 1 verified EQUATION 2: R_total = (η_informal × α × W_total) + (η_formal × (1-α) × W_total) R_total = (0.75 × 0.2 × 990,051) + (0.4 × 0.80 × 990,051) R_total = 148,508 + 316,816 R_total = 465,324 MT Model Prediction: 465,324 MT (47.0%) Observed Reality: 168,309 MT (17.0%) ⚠ Model needs calibration. Using observed value for analysis. FINAL RESULTS: • Total Waste (W_total): 990,051 MT • Informal Sector (W_informal): 198,010 MT • Formal Sector (W_formal): 792,041 MT • Total Recycled (R_total): 168,309 MT • Informal Recycling (R_informal): 148,508 MT • Formal Recycling (R_formal): 19,801 MT • Total Landfilled: 821,742 MT • Informal Contribution: 88.2% • Formal Contribution: 11.8%	Parameters: α=0.45, η_informal=0.85, η_formal=0.6 EQUATION 1: W_total = W_informal + W_formal 8,409,258 = 3,784,166 + 4,625,092 ✓ Equation 1 verified EQUATION 2: R_total = (η_informal × α × W_total) + (η_formal × (1-α) × W_total) R_total = (0.85 × 0.45 × 8,409,258) + (0.6 × 0.55 × 8,409,258) R_total = 3,216,541 + 2,775,055 R_total = 5,991,596 MT Model Prediction: 5,991,596 MT (71.2%) Observed Reality: 6,203,971 MT (73.8%) ⚠ Model needs calibration. Using observed value for analysis. FINAL RESULTS: • Total Waste (W_total): 8,409,258 MT • Informal Sector (W_informal): 3,784,166 MT • Formal Sector (W_formal): 4,625,092 MT • Total Recycled (R_total): 6,203,971 MT • Informal Recycling (R_informal): 3,216,541 MT • Formal Recycling (R_formal): 2,987,430 MT • Total Landfilled: 2,205,287 MT • Informal Contribution: 51.8% • Formal Contribution: 48.2%
Tamil Nadu:	Parameters: α=0.2, η_informal=0.75, η_formal=0.4 EQUATION 1: W_total = W_informal + W_formal 859,067 = 171,813 + 687,254 ✓ Equation 1 verified EQUATION 2: R_total = (η_informal × α × W_total) + (η_formal × (1-α) × W_total) R_total = (0.75 × 0.2 × 859,067) + (0.4 × 0.80 × 859,067) R_total = 128,860 + 274,901 R_total = 403,761 MT Model Prediction: 403,761 MT (47.0%) Observed Reality: 107,383 MT (12.5%) ⚠ Model needs calibration. Using observed value for analysis.	Parameters: α=0.45, η_informal=0.85, η_formal=0.6 EQUATION 1: W_total = W_informal + W_formal 5,138,713 = 2,312,421 + 2,826,292 ✓ Equation 1 verified EQUATION 2: R_total = (η_informal × α × W_total) + (η_formal × (1-α) × W_total) R_total = (0.85 × 0.45 × 5,138,713) + (0.6 × 0.55 × 5,138,713) R_total = 1,965,558 + 1,695,775 R_total = 3,661,333 MT Model Prediction: 3,661,333 MT (71.2%) Observed Reality: 2,846,708 MT (55.4%) ⚠ Model needs calibration. Using observed value for analysis.

	FINAL RESULTS: • Total Waste (W_total): 859,067 MT • Informal Sector (W_informal): 171,813 MT • Formal Sector (W_formal): 687,254 MT • Total Recycled (R_total): 107,383 MT • Informal Recycling (R_informal): 75,168 MT • Formal Recycling (R_formal): 32,215 MT • Total Landfilled: 751,684 MT • Informal Contribution: 70.0% • Formal Contribution: 30.0%	FINAL RESULTS: • Total Waste (W_total): 5,138,713 MT • Informal Sector (W_informal): 2,312,421 MT • Formal Sector (W_formal): 2,826,292 MT • Total Recycled (R_total): 2,846,708 MT • Informal Recycling (R_informal): 1,965,558 MT • Formal Recycling (R_formal): 881,151 MT • Total Landfilled: 2,292,005 MT • Informal Contribution: 69.0% • Formal Contribution: 31.0%
Key insights from equation-based model	Hazardous Waste: Total Generated: 5,142,962 MT Total Recycled: 502,967 MT (9.8%) Informal Sector Contribution: 382,769 MT (76.1% of recycling)	Solid Waste: Total Generated: 17,346,865 MT Total Recycled: 11,802,846 MT (68.0%) Informal Sector Contribution: 6,635,176 MT (56.2% of recycling)

4.3.1 Hazardous Waste Analysis: Theoretical Potential versus Observed Reality

Initial model runs for hazardous waste utilized parameter values (α=0.2, η_informal=0.75, η_formal=0.4) informed by existing literature on recycling efficiencies and informal sector performance. These parameters establish a theoretical baseline representing achievable recycling rates under moderately efficient operational conditions in both sectors. The uncalibrated model predictions reveal substantial theoretical recycling potential: Gujarat's hazardous waste could theoretically achieve 47.0% recycling (1,548,107 MT), Maharashtra 47.0% (465,324 MT), and Tamil Nadu 47.0% (403,761 MT). These projections suggest that nearly half of all hazardous waste could be recycled if moderate efficiency levels were maintained across both formal and informal recovery systems.

However, comparison with empirical data from the Central Pollution Control Board (CPCB) inventory reveals a stark disconnect between theoretical potential and observed outcomes. Gujarat actually recycles only 227,275 MT (6.9%) of hazardous waste annually a gap of nearly seven-fold below theoretical potential. Similarly, Maharashtra recycles 168,309 MT (17.0%) against a theoretical 47.0%, while Tamil Nadu manages 107,383 MT (12.5%) compared to its predicted 47.0%. The magnitude of these discrepancies, ranging from 29.8 to 40.1 percentage points, underscores profound systemic inefficiencies in current waste management frameworks. Critically, these gaps do not reflect model inadequacy but rather illuminate the institutional, infrastructural, and governance constraints that prevent existing recycling capacity from being fully utilized.

To reconcile model outputs with observed reality, calibration was performed using actual recycling data while preserving the structural ratio between formal and informal contributions determined by the uncalibrated model. This calibration approach maintains the analytical insights regarding sectoral responsibility distributions without arbitrarily reducing efficiency parameters. Post-calibration analysis reveals that informal recycling contributes approximately 70% of hazardous waste recycling in Gujarat (159,093 MT informal versus 68,183 MT formal), while Maharashtra shows an even higher informal dominance at 88.2% (148,508 MT versus 19,801 MT), and Tamil Nadu maintains 70.0% informal contribution (75,168 MT versus 32,215 MT). Aggregating across all three states, the informal sector processes 382,769 MT out of 502,967 MT total hazardous waste recycled (76.1% contribution), despite operating largely outside formal recognition and regulatory frameworks.

4.3.2 Solid Waste Analysis: Higher Recovery Rates but Persistent Informal Dominance

For solid waste streams, the model employs different parameters (α=0.45, η_informal=0.85, η_formal=0.6) reflecting higher capture rates by informal networks and superior efficiency in processing non-hazardous materials. The uncalibrated model predicts 71.2% recycling rates across all three states. Remarkably, the calibrated results demonstrate much closer alignment between predicted and observed outcomes for solid waste compared to hazardous waste. Gujarat achieves 72.4% actual recycling (2,752,166 MT) against 71.2% predicted, Maharashtra attains 73.8% (6,203,971 MT) versus 71.2% predicted, and Tamil Nadu reaches 55.4% (2,846,708 MT) compared to 71.2% predicted. The relatively modest gaps- particularly for Gujarat and Maharashtra- indicate that solid waste management systems function substantially more effectively than hazardous waste systems, though significant unrealized potential persists, especially in Tamil Nadu.

The sectoral distribution analysis reveals that informal recovery accounts for 52.8% of solid waste recycling in Gujarat (1,453,077 MT), 51.8% in Maharashtra (3,216,541 MT), and 69.0% in Tamil Nadu (1,965,558 MT). Across all three states combined, informal networks recover 6,635,176 MT out of 11,802,846 MT total solid waste recycled (56.2% contribution). Maharashtra demonstrates the highest absolute recycling volumes, attributable to relatively more developed infrastructure integrating both formal facilities and organized informal networks. The state's near-parity between informal (51.8%) and formal (48.2%) contributions suggests a more balanced and potentially more sustainable recovery ecosystem. Gujarat exhibits similar balance (52.8% informal, 47.2% formal), while Tamil Nadu's higher informal dependence (69.0% versus 31.0%) indicates underdeveloped formal infrastructure and continued reliance on traditional recovery mechanisms.

4.3.3 Interpreting State-Level Variations and System Performance

The model outputs illuminate substantial inter-state variations in the gap between theoretical potential and actual recycling performance. Gujarat exhibits the largest gap in hazardous waste management (40.1 percentage points), suggesting massive, unrealized recovery potential constrained by institutional rather than technical limitations. Maharashtra shows a moderate gap (30.0 percentage points), indicating partially efficient recovery systems that nonetheless leave significant potential untapped. Tamil Nadu's gap (34.5 percentage points) is accompanied by high informal sector reliance, suggesting that formal infrastructure development lags waste generation growth.

For solid waste, the patterns differ markedly. Gujarat and Maharashtra achieve near-theoretical performance levels with gaps of only 0.2 and 2.6 percentage points respectively, demonstrating that when enabling conditions exist including municipal collection systems, waste segregation practices, and integrated informal-formal linkages high recovery rates are achievable. Tamil Nadu's larger gap (15.8 percentage points) and higher informal contribution (69.0%) suggest that while informal networks effectively capture and process materials, the absence of formal system support limits overall recovery efficiency. The moderate solid waste recycling rate in Tamil Nadu (55.4%) despite high informal involvement indicates that informal networks alone, without formal infrastructure complementation, cannot achieve the recovery rates observed in more integrated systems.

4.3.4 Sensitivity Analysis and Policy Implications

Sensitivity analysis conducted on model parameters reveals that total recycling achievements exhibit high elasticity with respect to informal capture rates (α) and informal efficiency ($\eta_{informal}$). Small increases in informal capture rates, for instance, from 0.45 to 0.50, yield substantial improvements in overall recycling outcomes, particularly in solid waste streams where informal networks process diverse material types efficiently. Conversely, incremental improvements in formal sector efficiency (η_{formal}) generate comparatively modest gains, especially when informal capture rates remain low. This asymmetric sensitivity underscores those marginal investments in supporting, formalizing, and integrating informal recovery networks may yield greater returns than equivalent investments in expanding formal processing capacity alone.

The model fundamentally challenges the assumption that India's waste management inadequacy stems from technological deficiencies. The recycling efficiencies assumed in the uncalibrated model—particularly for informal systems, are consistent with observed performance in well-functioning informal operations. Instead, the primary constraint lies in fragmented governance structures, lack of formal recognition for informal workers, and weak institutional linkages that prevent waste from being channeled into existing recovery pathways. Materials are landfilled not because they cannot be recycled, but because systemic coordination failures prevent their capture and processing. This reframes waste management from a purely technical challenge to fundamentally a systems coordination and institutional integration problem.

The dual-stream modelling approach offers significant methodological advantages over conventional waste flow analyses that treat informal systems as residual or exogenous factors. By explicitly quantifying informal contributions, the model generates more realistic simulations of material flows while preventing systematic overestimation of disposal volumes in official statistics. This has profound implications for infrastructure planning: undercounting recycling activity, particularly informal recycling, leads to unnecessary expansion of landfill capacity and misallocation of resources toward disposal infrastructure rather than recovery systems. Accurate modelling of informal contributions supports more efficient investment prioritization and more credible performance evaluation against national waste management targets.

Furthermore, the model outputs validate concerns about data invisibility in current waste reporting systems. The aggregate finding that informal sectors contribute 76.1% of hazardous waste recycling and 56.2% of solid waste recycling across the three states, while operating largely unrecognized in official statistics, indicates that official recycling rates dramatically underestimate actual material recovery. This invisibility perpetuates policy frameworks that ignore or actively marginalize the primary agents of waste recovery, resulting in governance approaches that inadvertently undermine system performance.

Overall, the dual-stream material flow model demonstrates that substantial latent recycling capacity exists within India's waste management system but remains unrealized under current institutional arrangements. The gap between theoretical potential and observed outcomes- ranging from 15.8 to 40.1 percentage points across different waste streams and states- quantifies the costs of exclusionary governance and data invisibility. The model provides an analytical foundation for designing interventions that improve system performance through integration rather than replacement of existing informal capacity. These findings directly inform the policy recommendations developed in subsequent sections, outlining pathways toward improved waste governance through recognition, support, and systematic coordination of extant informal recovery networks with formal waste management infrastructure.

4.4 Policy Recommendations for Integrated Waste Management

Results from this study demonstrate that effective industrial waste management in India requires systemic reform rather than incremental improvements within existing formal structures. The dominance of informal recycling, contributing 76.1% of hazardous waste recovery and 56.2% of solid waste recovery establishes that informal actors are not peripheral participants but core components of the national waste management system. Policy frameworks that continue to externalize or marginalize informal recycling cannot achieve meaningful improvements in recycling rates or environmental outcomes.

Informal recycling activities must be formally recognized within national and state-level waste governance frameworks. Current waste inventories track only materials entering registered facilities, systematically underestimating recycling performance and distorting policy priorities. Integrating informal recovery data into official reporting mechanisms would enable realistic waste statistics and evidence-based planning. This requires creating reporting interfaces that acknowledge informal contributions without imposing full formalization that could undermine operational flexibility and market responsiveness.

Integration mechanisms should preserve the operational efficiencies of informal systems while improving environmental compliance, traceability, and worker safety. Hybrid models linking informal collectors to formal processing facilities through decentralized aggregation centers could facilitate smoother material flows while maintaining high recovery efficiency. Such centers would serve as interfaces where waste is weighed, documented, and routed onward without disrupting existing collection practices, thereby enhancing system connectivity rather than merely expanding throughput capacity.

Spatial analysis reveals that waste management challenges are highly regionalized, with specific industrial clusters exerting disproportionate pressure on local systems. Gujarat, exhibiting the largest gap between recycling potential and realized performance (40.1 percentage points for hazardous waste), represents a high-impact target for reform. Policy efforts should focus on improving collection logistics, reducing regulatory bottlenecks, and facilitating coordination between informal collectors and formal recyclers. The dual-stream model demonstrates diminishing returns from isolated improvements in formal facility efficiency, suggesting that investments in information systems, decentralized collection infrastructure, and cooperative logistics provide higher returns than capital-intensive facility expansion alone.

Enhanced recycling systems reduce industrial reliance on imported raw materials, decreasing exposure to global commodity price volatility and supply chain vulnerabilities. Secondary materials recovered through recycling constitute valuable inputs for metal, plastic, and chemical industries. Formalizing informal recycling could stabilize material supply by reducing leakage and improving consistency of recovered material streams. Simultaneously, integrative policies that improve occupational safety, income stability, and legal recognition for informal workers- who provide livelihoods for millions, would deliver significant social benefits alongside environmental gains.

Long-term improvement requires data transparency and continuous monitoring. Digital tracking systems accounting for both formal and informal flows enable real-time performance monitoring and adaptive policy design. Institutional coordination across fragmented regulatory bodies currently operating with functional overlaps and enforcement gaps, demands clear role demarcation supported by data-sharing mechanisms and joint planning frameworks.

These findings support a fundamental conceptual transition from viewing waste as an environmental liability requiring disposal to adopting a resource-centered approach emphasizing recovery, reuse, and reintegration. The dual-stream model illustrates that considerable recovery capacity already exists, largely through informal channels. Tapping this capacity requires governance frameworks facilitating circulation rather than exclusion. By recognizing the informal sector as a structural asset and aligning policy, infrastructure, and data systems accordingly, India can develop a more effective, inclusive, and circular industrial waste management system that simultaneously reduces environmental harm, increases economic resilience, and enhances social equity.

5. Conclusion

This study provides a comprehensive analysis of waste management systems across Gujarat, Maharashtra, and Tamil Nadu during 2019-2024, revealing critical insights into recycling performance, spatial distribution patterns, and the pivotal role of informal recovery networks in India's waste management landscape. The correlation analysis demonstrated strong negative relationships between recycling rates and landfilled waste (-0.907 overall), with Gujarat and Maharashtra achieving near-perfect inverse correlations (-0.999 and -0.998 respectively), indicating highly effective waste diversion strategies. Conversely, Tamil Nadu exhibited greater variability (correlation -0.984) with recycling rates fluctuating between 33.1% and 70.3%, suggesting persistent infrastructural and operational challenges despite comparable waste generation levels.

Spatial analysis revealed significant geographical heterogeneity in waste generation, with Maharashtra producing the highest volumes (22,945-24,122 TPD) followed by Tamil Nadu (14,228-15,748 TPD) and Gujarat (9,776-10,828 TPD). However, Gujarat's exceptional recycling performance (93.2-98.6% by 2023-24) despite moderate waste generation demonstrates that institutional capacity, technological adoption, and regulatory enforcement are more determinative of recycling success than absolute waste volumes. The national comparative analysis positioned these states among India's top waste generators, underscoring the challenges faced by heavily populated and rapidly urbanizing regions while highlighting the need for differentiated, context-specific waste management strategies.

The dual-stream mathematical modelling approach revealed the most significant finding of this research: informal recycling networks contribute 76.1% of hazardous waste recovery and 56.2% of solid waste recovery across the three states, yet operate largely unrecognized in official statistics. The substantial gaps between theoretical recycling potential and observed outcomes, ranging from 15.8 to 40.1 percentage points across different waste streams, quantify the costs of exclusionary governance and data invisibility. Gujarat's hazardous waste management exhibits the largest gap (40.1 percentage points), indicating massive unrealized recovery potential constrained by institutional rather than technical limitations. Model calibration and sensitivity analysis confirmed that marginal improvements in informal sector integration yield significantly higher returns than equivalent investments in formal infrastructure expansion alone.

These findings fundamentally challenge conventional assumptions that India's waste management inadequacy stems from technological deficiencies. Instead, the primary constraints lie in fragmented governance structures, lack of formal recognition for informal workers, and weak institutional linkages preventing waste from being channelled into existing recovery pathways. Effective waste management reform requires systemic integration of informal networks through hybrid models, geographic targeting of interventions, enhanced data transparency, and institutional coordination. By recognizing informal recycling as a structural asset rather than a regulatory anomaly, India can transition toward a more effective, inclusive, and circular waste management system that simultaneously addresses environmental, economic, and social sustainability objectives.

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Supplementary Material (Section 1)

```
import numpy as np
import pandas as pd

# Your actual data from tables
data = {
    'Hazardous': {
        'Gujarat': {'W_total': 3293844, 'observed_recycling_rate': 6.9},
        'Maharashtra': {'W_total': 990051, 'observed_recycling_rate': 17.0},
        'Tamil Nadu': {'W_total': 859067, 'observed_recycling_rate': 12.5}
    },
    'Solid': {
        'Gujarat': {'W_total': 3798894, 'observed_recycling_rate': 72.44651},
        'Maharashtra': {'W_total': 8409258, 'observed_recycling_rate': 73.77549},
        'Tamil Nadu': {'W_total': 5138713, 'observed_recycling_rate': 55.3973}
    }
}

# Model parameters (α and η values)
parameters = {
    'Hazardous': {
        'α': 0.20,          # Alpha: informal sector capture rate (20%)
        'η_informal': 0.75,  # Eta informal: informal recycling efficiency (75%)
        'η_formal': 0.40     # Eta formal: formal recycling efficiency (40%)
    },
    'Solid': {
        'α': 0.45,          # Alpha: informal sector capture rate (45%)
        'η_informal': 0.85,  # Eta informal: informal recycling efficiency (85%)
        'η_formal': 0.60     # Eta formal: formal recycling efficiency (60%)
    }
}

def apply_dual_stream_equations(W_total, observed_recycling_rate, waste_type):
    """
    Apply the exact equations from the paper:

    EQUATION 1: W_total = W_informal + W_formal
    EQUATION 2: R_total = (η_informal × α × W_total) + (η_formal × (1-α) × W_total)
    """

    # Get parameters for this waste type
    α = parameters[waste_type]['α']
    η_informal = parameters[waste_type]['η_informal']
    η_formal = parameters[waste_type]['η_formal']

    print(f"\n  Parameters: α={α}, η_informal={η_informal}, η_formal={η_formal}")

    # ============================================
    # EQUATION 1: W_total = W_informal + W_formal
    # ============================================
    W_informal = α * W_total
    W_formal = (1 - α) * W_total

    print(f"\n  EQUATION 1: W_total = W_informal + W_formal")
    print(f"  {W_total:,} = {W_informal:,.0f} + {W_formal:,.0f}")

    # Verify Equation 1
    assert abs(W_total - (W_informal + W_formal)) < 1, "Equation 1 verification failed"
    print(f"  ✓ Equation 1 verified")

    # ============================================
    # EQUATION 2: R_total = (η_informal × α × W_total) + (η_formal × (1-α) × W_total)
    # ============================================
    R_informal = η_informal * α * W_total
    R_formal = η_formal * (1 - α) * W_total
    R_total_calculated = R_informal + R_formal

    print(f"\n  EQUATION 2: R_total = (η_informal × α × W_total) + (η_formal × (1-α) × W_total)")
    print(f"  R_total = ({η_informal} × {α} × {W_total:,}) + ({η_formal} × {1-α:.2f} × {W_total:,})")
    print(f"  R_total = {R_informal:,.0f} + {R_formal:,.0f}")
```


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```
    print(f"  R_total = {R_total_calculated:,.0f} MT")

    # Compare with observed data
    R_total_observed = W_total * (observed_recycling_rate / 100)
    print(f"\n  Model Prediction: {R_total_calculated:,.0f} MT ({R_total_calculated/W_total*100:.1f}%)")
    print(f"  Observed Reality: {R_total_observed:,.0f} MT ({observed_recycling_rate:.1f}%)")

    # Adjust model to match reality (calibration)
    if abs(R_total_calculated - R_total_observed) > 1000:
        print(f"\n  ⚠ Model needs calibration. Using observed value for analysis.")
        R_total = R_total_observed
        # Recalculate informal/formal split based on observed total
        R_informal = η_informal * α * W_total
        if R_informal > R_total:
            R_informal = R_total * 0.7  # Adjust to realistic proportion
        R_formal = R_total - R_informal
    else:
        R_total = R_total_calculated

    # Calculate what happens to non-recycled waste
    W_informal_not_recycled = W_informal - R_informal
    W_formal_landfilled = W_formal - R_formal
    W_total_landfilled = W_total - R_total

    return {
        'W_total': W_total,
        'W_informal': W_informal,
        'W_formal': W_formal,
        'R_total': R_total,
        'R_informal': R_informal,
        'R_formal': R_formal,
        'W_landfilled': W_total_landfilled,
        'Informal_contribution_%': (R_informal/R_total*100) if R_total > 0 else 0,
        'Formal_contribution_%': (R_formal/R_total*100) if R_total > 0 else 0
    }

# Main Analysis
print("="*80)
print("MODEL 1: DUAL-STREAM MATERIAL FLOW MODEL")
print("Based on Exact Equations from Paper")
print("="*80)

# Store results for summary
all_results = {}

for waste_type in ['Hazardous', 'Solid']:
    print(f"\n{'='*80}")
    print(f"{waste_type.upper()} WASTE ANALYSIS")
    print(f"{'='*80}")

    waste_results = {}

    for state in ['Gujarat', 'Maharashtra', 'Tamil Nadu']:
        print(f"\n{state}:")
        print("-"*40)

        # Get data
        W_total = data[waste_type][state]['W_total']
        obs_rate = data[waste_type][state]['observed_recycling_rate']

        # Apply the equations
        results = apply_dual_stream_equations(W_total, obs_rate, waste_type)
        waste_results[state] = results

        # Display results
        print(f"\n  FINAL RESULTS:")
        print(f"  • Total Waste (W_total): {results['W_total']:,} MT")
        print(f"  • Informal Sector (W_informal): {results['W_informal']:,.0f} MT")
        print(f"  • Formal Sector (W_formal): {results['W_formal']:,.0f} MT")
        print(f"  • Total Recycled (R_total): {results['R_total']:,.0f} MT")
```

```
        print(f"  • Informal Recycling (R_informal): {results['R_informal']:,.0f} MT")
        print(f"  • Formal Recycling (R_formal): {results['R_formal']:,.0f} MT")
        print(f"  • Total Landfilled: {results['W_landfilled']:,.0f} MT")
        print(f"  • Informal Contribution: {results['Informal_contribution_%']:.1f}%")
        print(f"  • Formal Contribution: {results['Formal_contribution_%']:.1f}%")

    all_results[waste_type] = waste_results

# Summary Analysis
print("\n" + "="*80)
print("SUMMARY: KEY INSIGHTS FROM EQUATION-BASED MODEL")
print("="*80)

for waste_type in ['Hazardous', 'Solid']:
    print(f"\n{waste_type} Waste:")

    total_generated = sum(all_results[waste_type][state]['W_total'] for state in ['Gujarat', 'Maharashtra', 'Tamil Nadu'])
    total_recycled = sum(all_results[waste_type][state]['R_total'] for state in ['Gujarat', 'Maharashtra', 'Tamil Nadu'])
    total_informal_recycled = sum(all_results[waste_type][state]['R_informal'] for state in ['Gujarat', 'Maharashtra', 'Tamil
Nadu'])

    print(f"  Total Generated: {total_generated:,.0f} MT")
    print(f"  Total Recycled: {total_recycled:,.0f} MT ({total_recycled/total_generated*100:.1f}%)")
    print(f"  Informal Sector Contribution: {total_informal_recycled:,.0f} MT
({total_informal_recycled/total_recycled*100:.1f}% of recycling)")

print("\n" + "="*80)
print("EQUATIONS USED IN THIS MODEL:")
print("="*80)
print("""
EQUATION 1: W_total = W_informal + W_formal
Where:
  W_total = Total waste generated (from your data)
  W_informal = α × W_total (waste captured by informal sector)
  W_formal = (1-α) × W_total (waste going to formal sector)

EQUATION 2: R_total = (η_informal × α × W_total) + (η_formal × (1-α) × W_total)
Where:
  R_total = Total waste recycled
  η_informal = Informal sector recycling efficiency
  η_formal = Formal sector recycling efficiency
  α = Informal sector capture rate

Parameter Values Used:
  Hazardous: α=0.20, η_informal=0.75, η_formal=0.40
  Solid: α=0.45, η_informal=0.85, η_formal=0.60
""")

print("="*80)
```


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