International Journal of Original Recent Advanced Research
ISSN (Online): 3048-5479
Vol. 03, Issue 04, May 2026

SUSTAINABLE WASTE MANAGEMENT PRACTICES AND THEIR IMPACT ON URBAN ENVIRONMENTAL QUALITY

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ABSTRACT

Urban centres across developing and developed economies face mounting pressure from expanding waste volumes, and the manner in which municipalities respond to that pressure shapes air quality, water quality, soil health and public health outcomes in ways that are only partially understood. This study examines the relationship between sustainable waste management practices source segregation, composting, recycling, waste-to-energy conversion and landfill engineering and measurable indicators of urban environmental quality across a sample of 120 municipal wards drawn from six Indian cities of varying population size. Primary data were collected through structured household surveys (n=480), municipal records review, and field-based environmental sampling of air particulate matter, groundwater quality near disposal sites, and soil contamination indices. Statistical treatment involved descriptive analysis, Pearson correlation, and multiple regressions to isolate the contribution of specific practices to environmental quality scores while controlling for population density and municipal budget allocation. Findings indicate a statistically significant positive association between source segregation adoption and reduced PM2.5 concentrations near collection points, and a moderate inverse relationship between composting coverage and groundwater nitrate contamination. Waste-to-energy infrastructure, though present in only 18 of 120 wards, showed the strongest single-practice bivariate correlation with overall environmental quality index scores. Wards lacking formal segregation infrastructure recorded environmental quality indices roughly 34 percent lower than wards with mature segregation systems. These results extend earlier single-city studies by offering cross-city comparative evidence and by quantifying the differential weight of individual practices rather than treating sustainable waste management as a monolithic variable. The paper concludes that policy interventions targeting decentralised segregation and composting yield disproportionate environmental returns relative to capital-intensive waste-to-energy investment, particularly in mid-sized cities with constrained municipal budgets.

Keywords: *Sustainable waste management[1]; urban environmental quality[2]; source segregation[3]; composting[4]; waste-to-energy[5]; groundwater contamination[6]; municipal solid waste[7].*

1. INTRODUCTION

1.1 BACKGROUND AND RATIONALE

India generates an estimated 160,000 tonnes of municipal solid waste every day, and that figure climbs steadily as cities absorb rural migrants and disposable consumption habits spread beyond metropolitan cores. Waste that once decomposed on the margins of small towns now piles up at the edge of sprawling urban agglomerations, often without adequate segregation, treatment or disposal infrastructure. The consequences reach beyond aesthetics leachate from unmanaged landfills seeps into groundwater tables that supply drinking water to peri-urban populations, open burning of mixed waste releases particulate matter and dioxins into already compromised urban air, and organic fractions left to rot anaerobically generate methane, a greenhouse gas roughly 28 times more potent than carbon dioxide over a century timescale. Against this backdrop, sustainable waste management has moved from an environmental afterthought to a core determinant of urban livability. Yet policy discourse frequently treats sustainable waste management as a single undifferentiated intervention, obscuring the fact that source segregation, composting, recycling and waste-to-energy conversion operate through distinct causal pathways and produce different environmental returns. A municipality that invests heavily in a waste-to-energy plant while neglecting household-level segregation may see little improvement in groundwater quality even as it reports gains on paper. Understanding which specific practices drive which specific environmental outcomes therefore matters as much for budget allocation as for policy design, and this gap in disaggregated, empirically grounded evidence motivates the present study.

1.2 PROBLEM STATEMENT

Much of the existing literature on urban solid waste in India relies on single-city case studies, often confined to metropolitan areas such as Delhi, Mumbai or Bengaluru, and tends to measure environmental impact through proxy indicators collection efficiency, landfill diversion rate that do not directly capture ambient environmental quality. Few studies have attempted a cross-city comparison spanning cities of different population tiers, and fewer still have paired self-reported household practices with independently measured environmental parameters such as particulate matter concentration, groundwater nitrate levels and soil heavy-metal indices. This creates two problems. First, policymakers in mid-sized cities, where municipal budgets are considerably tighter than in metros, have little empirical guidance on which interventions yield the strongest environmental returns per rupee spent. Second, the absence of ward-level granularity in most existing datasets makes it difficult to isolate the effect of a specific practice from confounding variables like population density, income level or municipal governance quality.

1.3 OBJECTIVES AND SCOPE OF THE STUDY

The study pursues three specific objectives. First, to quantify the extent of adoption of five sustainable waste management practices source segregation, home and community composting, formal recycling channels, waste-to-energy conversion, and engineered landfill management across the sampled wards. Second, to measure three categories of environmental quality indicators at the ward level: ambient PM2.5 and PM10 concentrations near waste collection and transfer points, groundwater nitrate and coliform levels within a 500-metre radius of disposal sites, and a composite soil contamination index derived from heavy-metal concentrations. Third, to statistically model the relationship between practice adoption and environmental outcomes, controlling for population density, per capita municipal solid waste budget, and ward-level literacy rate as a proxy for civic awareness. The scope is deliberately bounded to six Indian cities selected to represent a spread of population size from roughly 300,000 to 4 million residents rather than attempting a nationally representative sample, since ward-level environmental sampling at scale imposes practical and cost constraints. The study does not attempt to model long-term trend data, confining itself instead to a cross-sectional snapshot collected over an eight-month field period. Within these bounds, the paper aims to offer municipal planners and environmental policy researchers a disaggregated, evidence-based account of which waste management interventions most efficiently improve measurable urban environmental quality.

2. REVIEW OF LITERATURE

Research on municipal solid waste management in India has evolved along three broad strands: engineering-focused studies on collection and disposal infrastructure, socio-behavioural studies on household segregation practices, and more recent environmental-monitoring studies that attempt to link waste practices to ambient quality indicators. Early work by [1] and [2] focused primarily on collection efficiency and transportation logistics in metropolitan wards, establishing that irregular collection schedules correlate with increased informal dumping and roadside burning. These studies, however, stopped short of measuring downstream environmental consequences, treating collection efficiency itself as the outcome variable rather than as a mediating factor.

A second strand of literature, exemplified by [3], [4] and [5], examined household-level segregation behaviour through survey instruments, finding that awareness campaigns produce short-term compliance gains that decay within 12 to 18 months absent sustained municipal reinforcement. [6] extended this line of inquiry to composting specifically, reporting that community-scale composting units in a mid-sized western Indian city reduced organic waste reaching landfills by approximately 40 percent in participating wards, though the study did not measure any corresponding change in groundwater or air quality. Studies directly linking waste management practices to environmental quality indicators remain comparatively scarce. [7] Measured leachate contamination around three unlined landfills in a northern Indian state and found nitrate concentrations in nearby borewells exceeding permissible limits by a factor of three, attributing this primarily to the absence of engineered liners rather than to upstream segregation practices. [8] Conducted air quality monitoring near waste transfer stations in a large metropolitan city and documented PM2.5 spikes coinciding with open burning events, though the study's single-city design limited generalisability. [9] and [10] have separately argued that waste-to-energy investment in Indian cities has often proceeded without adequate attention to feedstock composition, resulting in combustion inefficiencies when segregation upstream remains poor a finding with direct bearing on the present study's hypothesis that practice-specific effects, rather than aggregate sustainability investment, determine environmental returns.

International literature offers a somewhat more integrated picture. [11], working across European municipalities, developed a composite urban environmental quality index incorporating air, water and soil parameters and found that source-separated collection systems explained a larger share of variance in the index than downstream treatment technology, a finding this study's cross-city Indian sample seeks to test in a different institutional and infrastructural context. [12] Similarly reported, in a study of Southeast Asian secondary cities, that decentralized composting correlated more strongly with reduced surface water contamination than did centralized incineration capacity, though sample sizes in that study remained small. Within the Indian context specifically, [13] and [14] have both called for disaggregated, practice-level environmental impact studies rather than continued reliance on aggregate waste management performance indices published by municipal bodies, arguing that such indices often reward administrative reporting compliance rather than actual environmental outcomes. [15] offers the closest precedent to the present study's design, having paired household survey data with air quality monitoring across four wards in a central Indian city, though that study's small sample limits the statistical power available for regression-based inference.

Taken together, the literature suggests three gaps that this study addresses. First, most Indian studies remain confined to single cities, limiting cross-city comparative inference. Second, few studies pair self-reported practice data with independently measured environmental parameters across multiple domains air, water and soil simultaneously. Third, almost no study attempts to statistically disaggregate the relative contribution of individual practices to environmental outcomes while controlling for population density and municipal budget, treating sustainable waste management instead as an undifferentiated composite. The present study's six-city, 120-ward design, combined with multi-domain environmental sampling and regression-based disaggregation, is intended to close this specific gap.

3. METHODOLOGY

This study adopts a cross-sectional, mixed-methods design combining structured household surveys, municipal records review and field-based environmental sampling. Six Indian cities were purposively selected to represent a spread of population size, spanning approximately 300,000 to 4 million residents, and stratified by geographic region to reduce climate and soil-type bias in environmental readings. Within each city, wards were stratified by predominant waste management infrastructure presence or absence of source segregation programs, composting facilities, and waste-to-energy plants and 20 wards per city were randomly selected from within these strata, yielding a total sample of 120 wards. Within each selected ward, four households were randomly sampled for structured interview, producing a household-level sample of 480 respondents. Three categories of instruments were used. A structured household questionnaire, pre-tested on a pilot sample of 30 households and refined for clarity, captured self-reported waste segregation behavior, awareness of municipal composting or recycling programs, and perceived changes in local environmental conditions over a three-year recall period. Municipal records collection frequency logs, budget allocation statements and infrastructure inventories were obtained through official requests to each city's municipal solid waste management cell and cross-verified against ward-level infrastructure audits conducted by field teams. Environmental sampling comprised ambient PM2.5 and PM10 readings taken at fixed distances from waste collection and transfer points using calibrated portable monitors, groundwater samples drawn from bore wells within a 500-metre radius of disposal sites and tested for nitrate and coliform levels, and soil samples analyzed for a composite heavy-metal contamination index covering lead, cadmium and chromium.

Data were compiled into a ward-level dataset merging survey-derived practice-adoption scores with field-measured environmental indicators and municipal control variables population density, per-capita solid waste budget, and ward literacy rate. Descriptive statistics established baseline distributions across the six cities. Pearson correlation coefficients tested bivariate relationships between each practice variable and each environmental indicator. Multiple linear regression models were then estimated, with a composite environmental quality index as the dependent variable and the five practice-adoption variables entered alongside control variables, to isolate the independent contribution of each practice net of population density and budget effects. All analyses were conducted using a significance threshold of $p<0.05$, and multicollinearity among predictors was checked using variance inflation factors prior to final model specification.

4. DATA COLLECTION AND ANALYSIS

The combined dataset merges survey responses from 480 households, municipal infrastructure inventories, and field-measured environmental readings across 120 wards in six cities, labelled City A through City F in descending order of population, to preserve ward-level anonymity while retaining the population-tier variation the study design requires. Table 1 summarises the distribution of the sample and the infrastructure present in each city.

Table 1: Sample distribution and waste management infrastructure by city

City	Approx. Population	Wards Sampled	Households Surveyed	Wards with Segregation	Wards with Composting	Wards with WtE Plant
City A	4.1 million	20	80	14	9	5
City B	2.8 million	20	80	12	8	4
City C	1.2 million	20	80	9	6	3
City D	0.95 million	20	80	7	5	2
City E	0.48 million	20	80	4	3	2
City F	0.31 million	20	80	3	2	2
Total	—	120	480	49	33	18

Table 2 aggregates practice adoption rates by population tier, grouping cities A and B as large, C and D as medium, and E and F as small. A clear gradient emerges: larger cities show substantially higher adoption of every practice, with source segregation nearly four times more prevalent in large cities than in small ones.

Table 2: Practice adoption rate (%) by population tier

Population Tier	Segregation (%)	Composting (%)	Recycling (%)	WtE (%)	Engineered Landfill (%)
Large (A+B)	65	42	55	22	60
Medium (C+D)	40	27	35	12	45
Small (E+F)	17	12	15	10	25

Table 3 groups wards by segregation adoption level High, Medium, Low, and None and reports mean values for each environmental indicator alongside a composite Environmental Quality Index (EQI) scaled 0 to 100, with higher scores indicating better environmental condition. The gradient is stark: wards with no formal segregation recorded PM2.5 levels nearly double those of high-segregation wards, and an EQI roughly 34 percent lower.

Table 3: Mean environmental quality indicators by segregation adoption level

Segregation Level	Mean PM2.5 (µg/m³)	Mean GW Nitrate (mg/L)	Mean Soil Contamination Index	Mean EQI (0–100)
High	58	12.4	18.2	71
Medium	74	18.6	27.5	58
Low	91	26.3	38.9	46
None	108	34.7	47.1	37

Table 4 reports Pearson correlation coefficients between each of the five practice-adoption variables and the four environmental indicators. Source segregation shows the strongest relationship with PM2.5, composting the strongest relationship with groundwater nitrate, and waste-to-energy the strongest bivariate relationship with overall EQI despite its limited coverage.

Table 4: Pearson correlation matrix (practice adoption vs. environmental indicators)

Practice	PM2.5	GW Nitrate	Soil Index	EQI
Segregation	-0.61**	-0.54**	-0.49**	0.66**
Composting	-0.38*	-0.57**	-0.33*	0.52**
Recycling	-0.29*	-0.22	-0.31*	0.41**
Waste-to-Energy	-0.44**	-0.19	-0.27*	0.69**
Landfill Engineering	-0.35*	-0.48**	-0.52**	0.47**

* $p<0.05$, ** $p<0.01$.

Table 5 presents the multiple regression model, with EQI as the dependent variable. The overall model explains 58 percent of variance in EQI ($R^2=0.58$, Adjusted $R^2=0.55$, $F(7,112)=22.3$, $p<0.001$). Source segregation emerges as the strongest standardised predictor, followed by waste-to-energy adoption, with recycling falling short of conventional significance thresholds.

Table 5: Multiple regression results determinants of the Environmental Quality Index

Predictor	B	Std. Error	Standardised Beta	t	p
Segregation adoption	0.312	0.061	0.34	5.11	<0.001
Composting adoption	0.198	0.058	0.24	3.41	0.001
Recycling adoption	0.087	0.049	0.11	1.78	0.078
Waste-to-energy adoption	0.276	0.071	0.29	3.89	<0.001
Landfill engineering	0.142	0.055	0.16	2.58	0.011

Population density (control)	-0.061	0.028	-0.09	-2.18	0.031
Per-capita budget (control)	0.049	0.031	0.07	1.58	0.117
Constant	32.4	—	—	—	—

(R^2=0.58, Adjusted R^2=0.55, $F(7,112)$=22.3, $p<0.001$)

5. DISCUSSION

The regression results presented in Table 5 support the central premise motivating this study: that sustainable waste management is not a single lever but a bundle of distinct practices whose environmental returns differ meaningfully in size and mechanism. Source segregation emerged as the single largest standardised predictor of Environmental Quality Index scores (β=0.34, p<0.001), a result consistent with the bivariate correlations in Table 4, where segregation showed the strongest relationship with reduced ambient PM2.5 (r=-0.61) among all five practices. This pattern likely reflects the mechanism through which unsegregated waste ends up degrading urban environments mixed waste left at collection points is far more prone to informal open burning, since dry recyclables ignite readily and municipal workers often burn residual piles to reduce volume before transport. Composting adoption, meanwhile, showed its strongest relationship with groundwater nitrate levels (r=-0.57) rather than with air quality, a divergence that makes physical sense: composting diverts the organic fraction that would otherwise generate nitrogen-rich leachate at disposal sites, while doing comparatively little to affect what gets burned in the open. The waste-to-energy finding deserves particular attention, given its policy salience in Indian municipal planning. Despite operating in only 18 of the 120 sampled wards, WtE infrastructure showed the highest simple correlation with overall EQI (r=0.69) of any single practice, yet a somewhat smaller standardized regression coefficient (β=0.29) once segregation, composting and control variables were included. This gap between the bivariate and multivariate results suggests that WtE's apparent environmental benefit is partly attributable to co-location wards wealthy or well-governed enough to host a WtE plant also tend to have better segregation and collection systems already in place rather than to the WtE technology acting alone. This is a caution worth stating plainly: cross-sectional correlational data of this kind cannot fully separate a WtE plant's direct effect from the broader municipal capacity that made building one possible in the first place.

Recycling's comparatively weak and only marginally significant regression coefficient (β=0.11, p=0.078) is worth flagging rather than glossing over. It may reflect the informal, decentralised nature of recycling in most Indian cities, where informal scrap dealers handle a large share of dry waste recovery outside any system the household survey or municipal records could capture meaning the recycling-adoption variable in this study likely understates actual recycling activity rather than reflecting a genuinely weak practice-environment relationship. Population density's negative and significant coefficient (β=-0.09, p=0.031) confirms the expected finding that denser wards face a harder baseline environmental challenge independent of which waste practices they adopt, while per-capita budget's non-significant coefficient (p=0.117) suggests that money spent does not translate mechanically into environmental quality how it is spent appears to matter considerably more than how much.

5.1 COMPARISON WITH PRIOR STUDIES

These findings both extend and complicate the picture offered by earlier research. [11]'s European composite-index study found that source-separated collection explained a larger share of variance in urban environmental quality than downstream treatment technology a conclusion this study's Indian sample broadly supports, given segregation's leading standardised coefficient in Table 5. That convergence across such different institutional contexts, formal European municipal systems versus India's more hybrid formal-informal collection systems, suggests the underlying mechanism, reduced open burning and leachate generation, may operate somewhat independently of the specific regulatory environment in which segregation is implemented. At the same time, the magnitude of the effect differs: [11] reported segregation explaining roughly 45 percent of variance in the composite index alone, whereas this study's segregation variable, though the strongest single predictor, accounts for a smaller share of the model's total R^2 of 0.58 once composting and WtE are included, a difference plausibly attributable to India's WtE and composting infrastructure being more heterogeneously distributed across the sampled cities than in the more uniformly resourced European sample. The composting-groundwater relationship identified here ($r=-0.57$) is considerably stronger than what [6] found in the earlier community-composting study, though that earlier work measured landfill diversion volume rather than groundwater quality directly, making a like-for-like comparison difficult. What this study adds is a direct environmental-outcome measurement rather than a proxy, and the strength of the correlation suggests [6]'s diversion-volume findings likely understated composting's downstream environmental benefit, since diversion volume alone says nothing about what happens to the leachate that would otherwise have formed.

On waste-to-energy, this study's findings sit in productive tension with [9] and [10], both of whom raised concerns about combustion inefficiency when WtE plants receive poorly segregated feedstock. The present data cannot directly test combustion efficiency, but the gap observed between WtE's strong bivariate correlation with EQI and its more moderate multivariate coefficient is consistent with their broader concern: WtE's measured environmental benefit here appears partly confounded with the segregation quality of wards that host such plants, precisely the mechanism [9] and [10] warned about, even though their studies approached the question from an engineering-efficiency angle rather than a statistical-confounding one. Where this study's evidence differs from theirs is in degree rather than direction WtE still shows a positive, significant, independent association with EQI in the regression model ($\beta=0.29$, $p<0.001$) even after accounting for co-located segregation, suggesting the technology retains some environmental value net of confounding, contrary to a stronger reading of [9] and [10]'s scepticism. The leachate-focused findings of [7], who measured nitrate contamination around unlined landfills at levels three times the permissible limit, align closely with this study's None-segregation group in Table 3, where mean groundwater nitrate reached 34.7 mg/L against a typical permissible threshold of roughly 10–12 mg/L for drinking water, a comparable order of magnitude despite the different geography and sampling period. This convergence across two independently conducted studies, several years apart and in different states, lends some external validity to the finding that unmanaged or unsegregated waste streams produce broadly similar groundwater consequences regardless of regional soil or climate variation, though a more rigorous test of that claim would require multi-region panel data this study does not have.

Perhaps the most direct point of comparison is [15]'s four-ward study, which paired household survey data with air quality monitoring in a design methodologically closest to this paper's. [15] reported a PM2.5 reduction of roughly 22 percent in the highest-segregation ward relative to the lowest, a figure this study's six-city sample essentially replicates in direction though not in scale: the difference between High and None segregation groups in Table 3 amounts to a PM2.5 reduction of about 46 percent 58 versus 108 µg/m³, suggesting either that the relationship strengthens with a larger, more geographically diverse sample, or that the earlier study's particular baseline conditions moderated the effect it observed. Distinguishing between these two explanations is not possible with the data at hand, and represents a reasonable direction for future multi-city panel research building on both studies. Taken as a whole, this comparison suggests the present study's central contribution is less about discovering a wholly new relationship and more about disaggregating and quantifying, at a larger and more geographically varied scale, associations that earlier single-city or single-practice studies had identified only partially or indirectly.

6. CONCLUSION

This study set out to disaggregate the effects of five distinct sustainable waste management practices on measurable urban environmental quality across 120 wards in six Indian cities of varying size, moving past the tendency in prior literature to treat sustainable waste management as a single undifferentiated policy lever. The evidence gathered here supports a more specific conclusion: source segregation and composting, both comparatively low-cost and decentralised interventions, together account for a substantial share of the variance in the Environmental Quality Index, while waste-to-energy investment, though independently significant, appears to owe part of its apparent benefit to co-location with wards that already have strong segregation systems in place. For mid-sized and smaller cities operating under tighter municipal budgets, this suggests that scaling household and community-level segregation and composting programs is likely to yield larger environmental returns per rupee spent than capital-intensive waste-to-energy infrastructure, at least until segregation coverage reaches a level sufficient to supply clean feedstock to such plants. The non-significant effect of per-capita budget alone, contrasted against the strong effects of specific practices, reinforces a point municipal planners may find uncomfortable but useful: how waste management money is allocated across practices matters considerably more than the total amount allocated. This study's cross-sectional design and six-city scope limit its ability to establish causal direction or long-term trend, and future research employing panel data across a wider set of cities, alongside direct measurement of informal recycling activity, would help confirm whether the relationships identified here hold as segregation and composting infrastructure continues to expand across urban India.

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