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Income-Driven Transitions in Integrated Solid Waste Management: A Comparative Analysis of Treatment Strategies, Governance, and Recycling Systems in Global Cities

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Abstract

Rapid urbanization and economic development has increasingly exerted stress on urban solid waste management systems around the globe and clearly showed significant differences between treatment policies and institutional capacities between income levels. This paper analyzes income-based shifts in integrated solid waste management (ISWM) in 367 cities in the world with the cross-sectional design of quantitative research. Upon validation and normalization of treatments, 214 cities were assigned 5 typologies of strategies, that included Dump-Dependent, Landfill-Oriented, Mixed/Transition, Thermal-Dominant and Diversion-Oriented systems. Data were used to examine the differences in structure between waste generation, governance capacity, recycling performance, and system maturity using descriptive statistics, analysis of variance, ordinary least squares regression, multinomial logistic regression, and ordered logistic modeling. Findings indicate considerable differences in the distribution of strategies between low and high income groups and the low income cities tend to be dump dependent and the high income cities have higher propensity to implement engineered and recovery based systems. The scale of waste creation was considerably different between different strategy types, whereas the governance structure was varied, but not significantly related to the recycling performance. The logistic regression test was used to order and the results showed that the level of national income is a strong predictor of ISWM maturity. The results suggest that ISWM systems develop in accordance with the structural directions that are income-based, which implies the significance of combining institutional fortification, financial funding, and technological modernization to improve sustainable urban waste management.

Keywords: *Integrated solid waste management, Income-driven transitions, Municipal waste governance, Recycling performance, Urban sustainability*

1. INTRODUCTION

High rates of urbanization, population growth and economic development have greatly contributed to the production of municipal solid waste (MSW) across the globe. The generation of waste worldwide is expected to only increase along with growing population in urban areas and the shifting consumption trend, imposing an unprecedented burden on municipalities. The amount of waste generated across the world is predicted to grow significantly by 2050, especially in low- and middle-income nations in which the growth of infrastructure is failing to keep up with the growth of urban areas (Kaza et al., 2018). These structural trends also note the urgency of intensifying integrated solid waste management (ISWM) systems in cities of different economic capabilities. Waste mismanagement still prevails especially in the developing world where open dumping and unregulated disposal is still a daily occurrence in some regions. These circumstances pose environmental, social, and health risks, such as groundwater pollution, air pollution, and the exploitation of informal populations (Ferronato and Torretta, 2019). These inequalities reveal that waste management systems change unequally with income levels, which implies that there are structural changes related to economic development.

Integrated solid waste management is defined as a systemic approach that includes reduction of waste generation, collection, treatment, recovery and environmentally friendly disposal in one systemic structure. Recycling, composting and waste-to-energy technologies are becoming increasingly used to replace or supplement more traditional disposal-oriented systems. Waste-to-energy methods are becoming the new ways to decrease landfill addiction and produce renewable energy out of municipal waste flows (Beyene et al., 2018). Nevertheless, economic, institutional and technological constraints make the adoption of such technologies differ greatly across regions. Municipal waste in emerging economies is emerging as a potential renewable resource that can be used to achieve circular economy aims. Incineration, anaerobic digestion, and other energy recovery systems have improved technological capabilities in expanding resource valorization (Malav et al., 2020). However, the shift in the advanced recovery systems can be accompanied by high institutional structures, cost, and administrative skills, which might not be equally distributed among the income groups.

Technological changes in waste management are not the only changes but social and governance aspects are also involved. Social features of waste management, such as civic involvement, integration with informal sector, and institutional responsibility, play a crucial role in the performance of the system (Ma and Hipel, 2016). These factors of governance are crucial determinants of whether cities can be shifted away of disposal-dominant systems into more sustainable and circular forms. The waste management systems have implications on climate change and air pollution worldwide, not just locally. The use of circular waste management has proven to significantly lower the emission of greenhouse gases and other pollutants compared to the traditional systems of disposal (Gómez-Sanabria et al., 2022). This points to the need to study how the treatment strategies vary across cities and how structural changes can impact environmental performances.

Life cycle assessment (LCA) has become an important methodological approach to assess the sustainability of systems of waste management. General evaluations indicate that waste system environmental performance is based on treatment mixes, technological effectiveness, and recovery rates of materials (Ceraso and Cesaro, 2024). Comparative LCA research also indicates that optimized settings can cut emissions and enhance resource efficiency by a large margin compared to the standard disposal operations (Khandelwal et al., 2019). Equally, systematic reviews of the waste-to-energy valorization technologies state the relevance of integrated assessment frameworks to determine trade-offs between the environmental advantages and the operational limitations (Dastjerdi et al., 2021). When integrated with energy recovery systems or composting systems, carbon footprint of waste systems indicated that the lifecycle emissions could be decreased by diversion of organic waste and better treatment pathways (Maalouf and El-Fadel, 2018). These results highlight the importance of knowing structural variations in treatment plans in terms of income.

The governance structures play a major role in influencing the results of the waste systems. Comparative case studies show that those cities that have better institutional coordination and policy frameworks are likely to have more advanced practices of waste stewardship (Lee-Geiller and Kuttling, 2021). The performance of recycling is not only affected by the institutional arrangements, regulatory enforcement, and long-term planning mechanisms but also on the maturity of the overall ISWM systems. The structural challenges that affect developing economies, such as limited funding, institutions, and lack of technological infrastructure, continue to restrict the process of moving to integrated systems (Kumar et al., 2017). Such governance and economic inequalities support the hypothesis that ISWM systems develop along income-based lines to open dumping, engineered landfilling, then to recovery-focused and circular systems.

The main purpose of this research is to consider income-based changes in solid waste management (ISWM) systems of global cities. In particular, the research paper focuses on categorizing cities as per their prevailing waste management approaches, compare the disparity in the amount of waste generated and governance systems in key types of strategies, and assess how economic development correlates with the maturity of ISWM. Combining treatment pathway analysis, governance indicators and comparing income level, the study attempts to establish structural patterns that interpret variation in recycling performance and evolution of the system in general.

2. METHODOLOGY

2.1 Study Design and Data Source

The study utilized cross-sectional quantitative research design to test integrated solid waste management (ISWM) strategies in global cities. It was analyzed using a city-level dataset of 367 municipalities and 113 variables. The dataset involved numeric and nominal pointers that encompass waste generation, treatment routes, waste composition, governance and legal framework, and economic classification. The city was the unit of study and all statistical operation was done on the basis of the city level. The data set included both treatment variables and institutional variables needed to measure structural differences in ISWM settings. This allowed comparing treatment systems, conditions of governance, and economic context among cities (Arman, 2021).

2.2 Data Cleaning and Sample Validation

The preparation of the data was done in several steps so as to have internal consistency and analytical reliability. First, cities that have complete data of the amount of municipal solid waste produced were located. Among 367 cities, 325 of them had the available data about MSW generation in tons per year. Afterwards, consistency of treatment pathways was assessed. The percentage shares of the total reported treatment and disposal pathways of a city were added to measure internal coherence. Those with treatment totals between 80 percent and 110 percent were considered as retained to provide some variations in reporting. Those cities not in this range were not further categorised in strategy. Following this validation exercise, there were 214 cities that were left in the final analysis sample. In these cities the share of treatment was brought to a balance by treating all the cities to the same amount which was 100 percent. This normalization made comparisons between cities possible and, additionally, made it possible to classify strategies.

2.3 Variable Specification

The total city solid waste was calculated in tons per year and the skew in regression was addressed using both the raw and Log-transformed data. The time of waste was evaluated in percentages of large material fractions, such as organic waste, paper, plastic, and glass, metal, and so on. The percentage shares of disposal and recovery options defined the treatment pathways, and it was upon these that classification of ISWM strategies was based on after normalization. A governance index was created based on nine institutional and legal indicators which were measured between 0 and 1 with high values indicating a good governance capacity.

2.4 ISWM Strategy Classification

After validation and normalization of treatment shares, cities were categorized into 5 types of the Integrated Solid Waste Management strategy. Dominant treatment pathways and general system organization were the basis of classification. These five systems were categorized as Dump-Dependent, Landfill-Oriented, Mixed/Transition, Thermal-Dominant, and Diversion-Oriented systems. Descriptive comparisons, multinomial regression analysis and ordinal ISWM maturity variable of ordered logistic regression model were all based on this categorical classification variable.

2.5 Statistical Analysis

Python-based libraries were used in all statistical analyses. The values of central tendency and dispersion were used to summarize waste generation and treatment shares, waste composition and the values of the governance index using descriptive statistics. One-way ANOVA tests were used to test the difference in waste generation and index of governance between the ISWM strategy types. One of the two commonest least squares (OLS) models was used to evaluate the relationship between governance and recycling performance with total waste generation as a dependent variable and log-transformed generation with HC3 robust standard errors. Furthermore, the multinomial logistic regression was estimated to determine the relationship between income level and the type of ISWM strategy with the statistics of model fitting.

3. RESULTS

3.1 Dataset Overview and Sample Refinement

It contained a city level dataset having 367 cities and 113 variables. Out of them, 70 variables were numeric and 43 categorical. After the data cleaning and preparation procedures, 325 cities were found to contain the information about the total municipal solid waste (MSW) generation. Internal consistency was then done through treatment pathway validation. Cities whose treatment shares ranged between 80% and 110% before normalization were kept and the final analysis sample ended with 214 cities. Following normalization, treatment percentages added up to 100% in all the retained cities, which verifies internal consistency of the treatment structure. Treatment percentages were computed using descriptive statistics before validation and the mean value was found to be 64.63% (SD 47.31) with a range of 0% to 120. The sums of composition percentage had the mean of 80.16% (SD = 39.85), and the highest value of 114. These figures indicate that there exists variability in the completeness of reporting across cities before being filtered. Table 1 reports the core descriptive statistics of treatment variables, composition variables as well as total MSW generation.

Table 1. Core Descriptive Statistics for Treatment, Composition, and MSW Generation Variables

Variable	N	Mean	SD	Min	Median	Max
Organic waste (%)	265	46.12	17.69	1.05	48.40	85.00
Paper/cardboard (%)	264	12.62	8.58	0.08	11.00	50.00
Plastic (%)	258	11.30	6.14	0.01	11.00	48.00
Glass (%)	245	4.06	4.04	0.00	3.00	32.58
Metal (%)	242	2.84	2.90	0.01	2.00	25.70
Total MSW generated (tons/year)	325	584,499.50	1,006,116.00	872.35	219,000.00	7,903,000.00

As Table 1 presents, the biggest proportion of municipal waste in reporting cities is organic waste, with an average of 46.12%. Paper/cardboard and plastic fractions were next with glass and metal accounting smaller. There was also a significant variability in total MSW generation, with a high of 7.9 million tons/year, which shows that cities varied significantly within the dataset.

3.2 ISWM Strategy Typologies

The classification of cities was developed into five types of treatment pathways based on the predominant treatment strategy and the validation and normalization of treatment shares. Table 2 shows the spread of cities in these types of strategies. Before the distribution is given, it is mentioned that classification was done after ascertaining that treatment shares amounted to 100% of all 214 retained cities.

Table 2. Distribution of ISWM Strategy Types (n = 214)

Strategy Type	Number of Cities	Percentage (%)
Dump-Dependent	67	31.31
Landfill-Oriented	64	29.91
Mixed/Transition	63	29.44
Thermal-Dominant	11	5.14
Diversion-Oriented	9	4.21

Table 2 indicates that Dump-Dependent systems constitute the highest number of cities (31.31%), then there are Landfill-Oriented (29.91%) and Mixed/Transition systems (29.44%). Thermal-Dominant systems and Diversion-Oriented systems are relatively lower fractions of the sample. Figure 1 presents the general picture of the distribution of the ISWM strategy types.

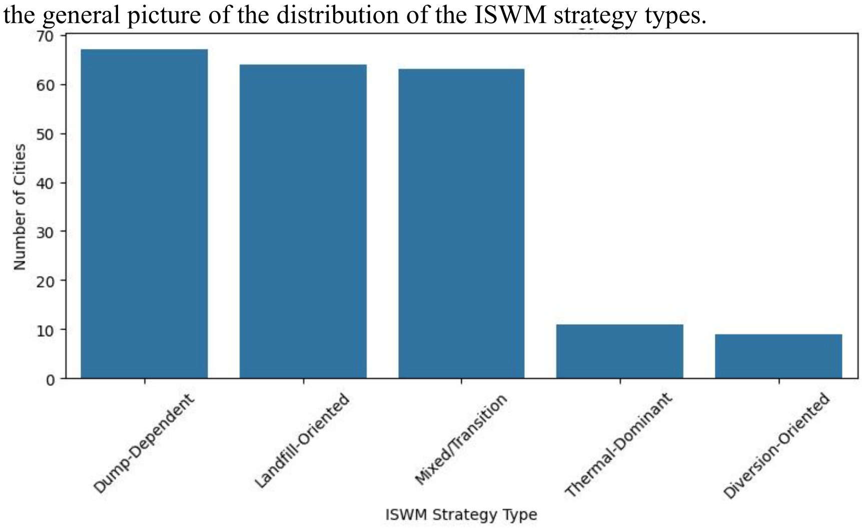

Figure 1. Global Distribution of ISWM Strategy Types

The frequency of the various strategies types in the 214 successful cities that had been checked is presented in Figure 1. The figure above validates the trend in Table 2, with disposal-oriented systems (dumping and landfill) taking the largest percentage of the observed configurations.

3.3 Strategy Distribution Across Income Levels

To test the structural variation of economic contexts, the types of the ISWM strategies were cross-tabulated by national income level. Table 3 shows the percentage distribution in each income category. Prior to tabulating the table, it is mentioned that percentages are the within-income-group distributions.

Table 3. ISWM Strategy Distribution by Income Level (% within income group)

Income Level	Diversion-Oriented	Dump-Dependent	Landfill-Oriented	Mixed/Transition	Thermal-Dominant
HIC	4.55	4.55	36.36	29.55	25.0
LIC	0.00	43.33	16.67	40.00	0.0
LMC	5.88	44.71	17.65	31.76	0.0
UMC	3.64	25.45	50.91	20.00	0.0

Table 3 shows that there is variation in strategy composition with income groups. The category of LIC and LMC has greater Dump-Dependent and Mixed/Transition systems. The UMC cities are majorly Landfill-Oriented with the HIC cities having a higher proportion of Landfill-Oriented and Thermal-Dominant systems. The inequality in income distribution is further illustrated in Figure 2.

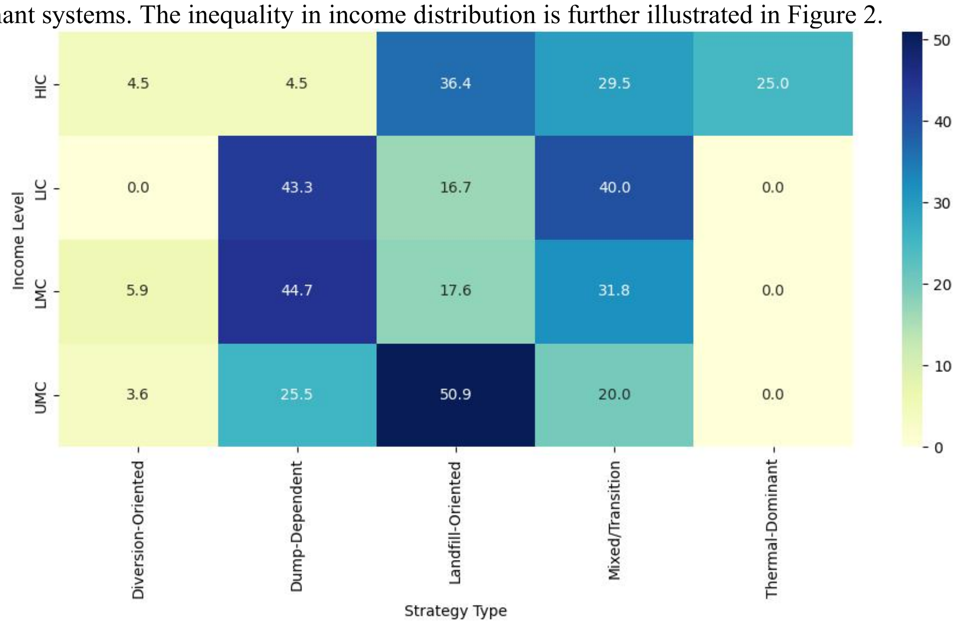

Figure 2. ISWM Strategy Distribution by Income Level

Figure 2 gives a graphical depiction of the percentage level of ISWM plans in the individual income groups, and further supports the trends in Table 3.

3.4 Waste Generation Across Strategy Types

The level of waste generation was compared in terms of ISWM strategies. Table 4 represents descriptive statistics. Before introducing the table it is stated that the values of MSW generation are measured in tons per year.

Table 4. Annual MSW Generation by ISWM Strategy Type (tons/year)

Strategy Type	N	Mean	Median	SD	Min	Max
Diversion-Oriented	9	1,484,247.78	547,500.00	1,557,881.68	72,000	4,190,000
Landfill-Oriented	64	1,057,621.77	478,192.88	1,481,294.16	2,701	7,903,000
Thermal-Dominant	11	805,637.09	399,133.00	1,017,426.47	25,500	3,560,990
Mixed/Transition	63	579,659.26	291,703.71	766,952.92	5,515	3,062,350
Dump-Dependent	67	390,310.91	109,500.00	853,447.11	872.35	5,500,000

Table 4 indicates that the average MSW growth is different between the types of strategies; Diversion-Oriented and Landfill-Oriented systems have a higher average generation values than Dump-Dependent ones. ANOVA test showed that the generation of MSW among the different types of strategies was statistically different (F = 4.375). Figure 3 illustrates the spread of MSW generation within strategy types.

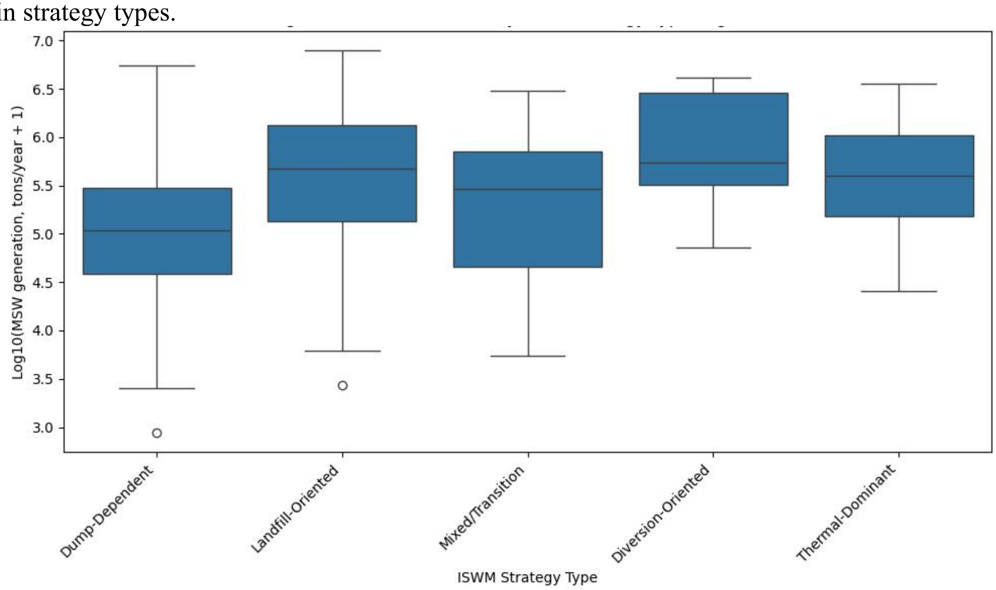

Figure 3. MSW Generation by ISWM Strategy Type

Figure 3 shows the change in the level of waste generation of various types of strategies, which indicate the difference between dispersion and central tendency, as explained in Table 4.

3.5 Governance Index and Strategy Types

An index of governance was created among the 214 cities that were validated. The summary statistics of the governance index were as follow; mean = 0.4798, SD = 0.2855, minimum = 0, and maximum = 1. Table 5 shows the scores in governance across the types of strategies.

Table 5. Governance Index by ISWM Strategy Type

Strategy Type	Mean	Median	SD
Diversion-Oriented	0.630	0.667	0.289
Dump-Dependent	0.619	0.667	0.267
Thermal-Dominant	0.485	0.444	0.255
Mixed/Transition	0.411	0.333	0.274
Landfill-Oriented	0.380	0.333	0.259

The outcome of ANOVA showed that there were significant differences in the governance index in different strategy types (F = 8.487; p = 0.0). The governance distribution by the category of strategies is shown in Figure 4. This Figure displays variation in governance index scores among the five strategy types.

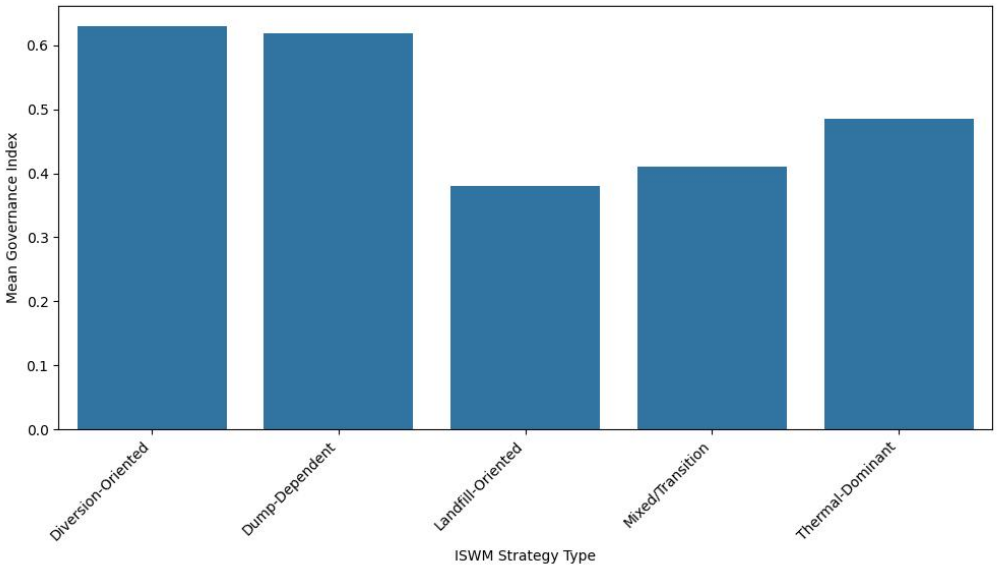

Figure 4. Governance Index by ISsWM Strategy Type

3.6 Governance and Recycling Performance

An OLS regression model was estimated using two dependent variables waste treatment recycling percentage. The predictors incorporated in the first model were the governance index and total MSW produced (tons/year). The model yielded $R^2 = 0.001$, F-statistic = 0.04841, and Prob(F-statistic) = 0.953. Coefficients were as follows: governance_index = -1.2039 ($p = 0.837$) and annual total municipal solid waste (MSW) generated by a city = -3.413e-07 ($p = 0.810$). In the second model, log-transformed generation and robust (HC3) standard errors were applied. The model produced $R^2 = 0.007$, F-statistic = 0.7509, and Prob(F-statistic) = 0.474. Coefficients were governance_index = -0.3351 ($p = 0.943$) and log_generation = 0.8617 ($p = 0.273$). These regression results are summarized in Table 6.

Table 6. OLS Regression Results for Recycling Percentage

Model	R^2	F-statistic	Prob(F)
Model 1	0.001	0.04841	0.953
Model 2	0.007	0.7509	0.474

The relationship between governance index and recycling share is illustrated in Figure 5.

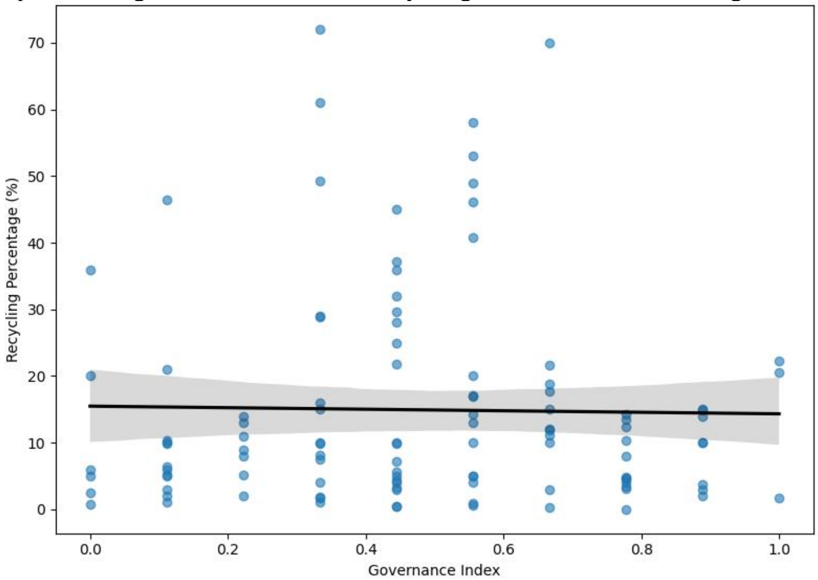

Figure 5. Governance Index and Recycling Percentage

The scatter plot of the values of the governance index versus the percentage of recycling and fitted regression line is shown in Figure 5.

3.7 Multinomial Logit Model

A multinomial logit model was estimated with strategy type as the dependent variable. The model reported a Pseudo R^2 of 0.1318 and Log-Likelihood of -254.61. The likelihood ratio test produced LLR p-value = 1.337e-11. However, the model did not converge, and maximum iteration limits were exceeded.

3.8 Ordered Logistic Regression of ISWM Maturity

An ordered logistic regression model was estimated using ISWM maturity level as the dependent variable. The model converged successfully with Log-Likelihood = -257.63, AIC = 527.3, and BIC = 547.5. Coefficients were as follows: LIC = -2.2863 ($p = 0.000$), LMC = -2.1598 ($p = 0.000$), and UMC = -1.0959 ($p = 0.004$). Threshold parameters were 1/2 = -2.4011 ($p = 0.000$), 2/3 = 0.3517 ($p = 0.002$), and 3/4 = 0.7394 ($p = 0.000$). These results are summarized in Table 7.

Table 7. Ordered Logistic Regression Results

Variable	Coefficient	p-value
LIC	-2.2863	0.000
LMC	-2.1598	0.000
UMC	-1.0959	0.004

The projected maturity levels of ISWM by income groups are demonstrated in Figure 6. The results of the ordered logistic regression were presented in a graphical manner in figure 6 based on income categories.

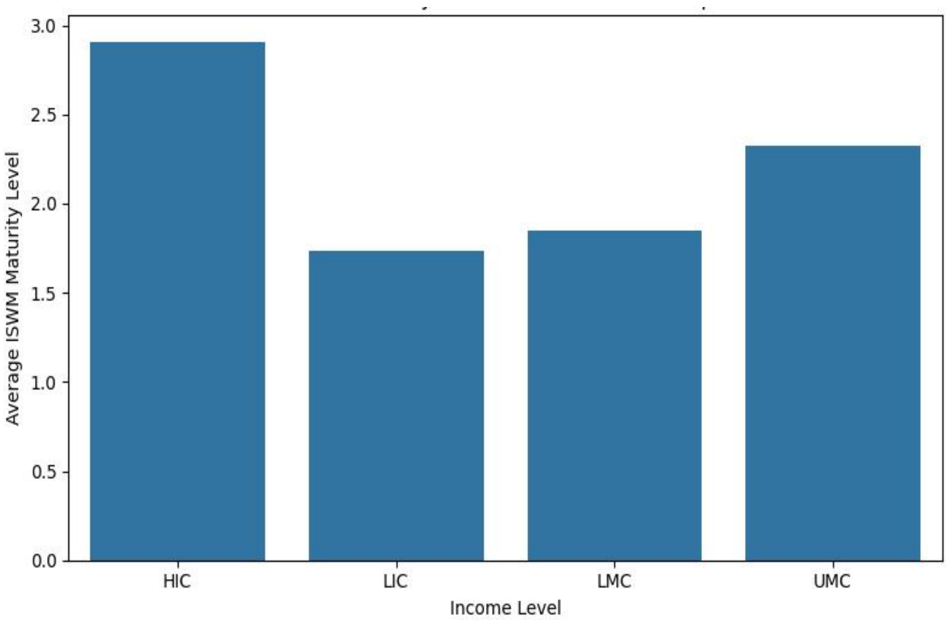

Figure 6. Predicted ISWM Maturity by Income Level

4. DISCUSSION

This research has got empirical evidence that there are income-driven transitions in integrated solid waste management systems. The cities with low-income conditions were largely identified as dump-dependent or transitional, and the cities with high-income rates depicted the more common configurations of landfills, thermal and diversion-based. These patterns of structure are consistent with the latest review of global trends in municipal solid waste, which states that socio-economic development has been a major factor defining the effectiveness of the systems and technological progress (Maalouf and Mavropoulos, 2023). With the growth in economies, cities seem to have the capacity to transform disorganized disposal into engineered and recovery-based systems. The close correlation between income level and ISWM maturity as defined by ordered logistic modeling is in line with larger global studies that socio-economic development is linked to waste system performance (Velis et al., 2023).

Governance was also a notable distinction factor between strategy types, but it did not provide a statistically significant relationship with recycling performance in regression models. The statistical difference in governance index scores among the ISWM categories supports the argument that institutional capacity results in waste management. Regulation issues, especially in developing settings, tend to constrain successful policy adoption, and drag on the achievement of sustainable development objectives (Rodić and Wilson, 2017). Nevertheless, the lack of direct correlation between governance index and recycling share indicates that the formal institutional presence is not always likely to manifest better diversion results. Recent literature highlights that the effectiveness of governance relies on the contextual adjustment and institutional design based on locality, and not just regulatory presence (Sasahara et al., 2024). This view can be used to understand why not all cities that were dump-dependent had poor governance index scores, which means that institutional structures can exist without being converted into operational efficiency and technological upgrade. Additional support through comparative governance research indicates that models of governance play an important role in the performance variance across local authorities (Novais and Tavares, 2025). This is supported by the current findings, which suggest that quality governance should be accompanied by financial, technological, and social-economic ability to produce quantifiable changes in the performance of recycling.

The large variance in the amount of waste produced with different types of ISWM strategies underscores the importance of scale in the development of the system. The cities which had elevated generations were more likely to take landfill-based or advanced treatment systems, indicating that better amounts of waste might be worth investing in engineered structures. This fact corresponds to integrated network design strategies that focus on the optimization of scale when designing municipal waste systems (Yousefloo and Babazadeh, 2020). Heavy volumes of waste can offer economies of scale enabling the investment of sanitary landfills, incineration plants, or composting plants. Concurrently, systemic redesign is becoming more and more popular in circular economy frameworks in order to unlink waste production with the environment (Tsai et al., 2020). The prevalence of the disposal-oriented systems in the setting with low income shows that the process of the circular transitions is not global. This imbalance indicates the financial limitations as well as the structural impediments which slows down the implementation of resource recovery models.

The small share of thermal dominant and diversion oriented cities in the sample highlights the low level of spread of advanced and efficient waste-to-energy and resource recovery technologies. WtE technologies provide the opportunities of sustainable resource management and landfill diversion, but their introduction presupposes the high financial investment and technical skills (Varjani et al., 2022). The findings indicate that these kinds of technologies are still concentrated in economic high-developed settings. New studies emphasize waste-to-energy technology as a promising element of sustainable materials management when considered as a part of generally Circular strategies (Soni et al., 2025). But until governance capacity and stable financial frameworks are in place, technological adoption may not go much higher. The maturity gradient of this study that is based on income shows that technological diffusion is not independent but follows general economic transitions. Carbon credit systems and optimization tools also represent how the superior waste management systems can enhance environmental performance, should the institutional and financial situations allow (Maalouf and El-Fadel, 2020). These tools are more likely to be available in places with higher income levels and are a reinforcement of economic groups differences in system maturity.

The implications of findings on the sustainable urban development are dramatic. Although technological innovation has been the more important topic in the waste management dialogue, this paper lends importance to the structural contribution of income and institutional capacity in defining shifts within the systems. Circular waste management has become the focus of policy development, but its adoption is not evenly distributed throughout the regions (Tsai et al., 2020). The key to closing this divide is focused investment, strengthening of governance and the situational planning. Finally, the data indicates that the ISWM systems develop in accordance with the structural patterns that can be defined by the economic growth, governance formations, and the volume of waste.

5. CONCLUSION

The income-based changes in the integrated solid waste management (ISWM) systems in world cities. Basing the treatment strategies of municipalities on 5 dominant categories and correlating these patterns with income status, governance capacity and the scale of waste generation, the results demonstrate the patterns of structural structure in system development. The former means that lower-income cities continue to rely predominantly on open dumping and transitional arrangement, whereas higher-income settings are characterized by the increased use of engineered landfills, thermal treatment and diversion-based approaches. Whereas governance forms varied greatly between different types of strategies, institutional presence did not forecast recycling performance meaning that formal structures should be anchored by financial capability and operational efficiency. The level of waste generation was also found to be a significant factor with larger generation cities being more inclined to embrace advanced infrastructure. The findings indicate that maturity of ISWM follows economically mediated patterns other than solitary technological implementation. Sustainable and circular waste systems are therefore achieved through combined policy strategies that integrate institutional fortification, financial resources and solutions that are based on context. The results can help to comprehend the dynamics of organization of global municipal waste transitions and form the basis of specific policy intervention in the fast urbanizing environment.

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