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Evaluating Recycling Efficiency and Material Recovery Pathways for Sustainable Waste-to-Value Systems Using Global Waste Management Data

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Abstract

Globally, waste-management systems are mainly reliant on disposal, although there are significant recoverable materials in municipal solid waste. The recycling efficiency and material-recovery pathways were assessed based on country-level global waste-management data on the amounts of waste generated, waste composition, recycled, composted, incinerated, land filled, and dumped. The recovery potential and factors associated with recycling performance were assessed using descriptive statistics, regional and income-group comparisons, correlation analysis and multiple regression. This analysis revealed that the organic waste was the largest proportion of waste and dry recyclable waste also a significant proportion. There is however a significant recovery gap as mean recycling and composting rates are far below the estimated recovery potential. Generally, high-income countries' waste recycling and disposal dependency were higher than low-income countries' recycling rates and their dependency on open dumping, despite lower waste per capita, in the latter. Some regional differences were also observed, depending on the level of infrastructure, governance, source separation and the secondary-material markets. Economic capacity and dry-material recovery potential were positively associated with recycling, whereas disposal dependency was negatively associated with recycling. Among all these factors, in the regression model, disposal dependency had the largest effect on the performance of the recycling process. The study ends on the ambitious conclusion that sustainable waste-to-value transitions demand systems that integrate source segregation, material recycling, biological waste treatment, energy recovery and controlled residual disposal. Avoiding disposal dependency is a key step to making resource use more efficient and supporting the global circular waste-management systems.

Keywords- recycling efficiency, material recovery, waste-to-value, circular economy, municipal solid waste

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1. INTRODUCTION

Urbanization, population growth, consumer habits and increased consumption have contributed to the increased production of municipal solid waste (MSW) globally. In many countries waste systems continue to be based on waste collection and disposal, and are causing environmental pressures from landfilling, open dumping, greenhouse-gas emissions, resource depletion, and uncontrolled pollution. In developing economies, low infrastructure investment, institutional capacity and enforcement are often limiting environmentally friendly waste management practices, with impacts particularly strong in this context (Abubakar et al., 2022). Circular-economy is an approach that aims to break the linear economy of extraction, use and disposal with systems that keep materials in use. Waste prevention, reuse, recycling and secondary raw-market are being more and more recognized as key pillars of a cleaner and more competitive economy in European policy (Plan, 2020). Despite this, recent analysis suggests that there is an uneven rate of progress in the use of circular materials and waste recovery by region and economic sector (European Environment Agency, 2024). While recycling rate is used to measure circularity, it does not completely account for material quality, avoided disposal, recovery efficiency or the actual replacement of virgin resources (Fellner & Lederer, 2020). A life-cycle approach to waste management offers a more comprehensive perspective on the environmental impacts of waste treatment pathways and their respective benefits. Combining source separation, recycling, composting, energy recovery and controlled disposal in an integrated approach can minimize environmental impacts when technologies are adapted to local waste characteristics and institutional conditions (Iqbal et al., 2020). Through a review of global evidence, it has been identified that coordinated pathways for recovering recyclable dry matter, biodegradable fractions, energy, nutrients and construction resources is essential for effective valorization (Kafle et al., 2025).

All-component recovery strategies could also help enhance environmental and economic outcomes, by reducing the volume of waste that has to be disposed of and maximizing the value of recovered materials from mixed waste streams (Liang et al., 2022). Municipal waste (MW) has significant bioenergy potential, especially in cases where there is a high share of organic waste and low traditional recycling rates (Nanda & Berruti, 2021). But the world is not equal with respect to analytical and technological skills and the best of these is found in high-income countries (Ndou & Rampedi, 2022). Hence, the need for governance models that link local infrastructure, financial plans, stakeholder involvement and circular-economy targets in cities and regions (OECD, 2020).

An extra challenge is the international production, trade, consumption and disposal systems for plastic waste, which are influenced by economic policy and global governance arrangements (Barrowclough & Birkbeck, 2022). In the long-term, more robust measures are anticipated to be needed to limit plastic pollution and the associated leakage to the environment across the globe (Sonke et al. 2025). Another precondition for successful implementation of a circular economy is the coordination of stakeholders, institutional learning and harmonization of public, private, and community interests (Sarna & Plotnikova, 2025). Transitions are still limited in emerging economies due to the absence of formal collection system, segregation at a low level, weak governance and low investments in recovery infrastructure (Onungwe et al., 2023). However, there are technologically suitable pathways to recover municipal, agricultural, and industrial wastes as energy, fertilizers, food related inputs, and construction materials (Peng et al., 2023).

Contamination and mixing of waste are still key points of segregation quality since they make recycling and waste-to-energy conversion less feasible (Rashad et al., 2025). The other direct benefits that circular waste management can bring to targets for sustainable-development include pollution reduction, resource conservation, livelihood development and strengthening of post-crisis recovery systems (Sharma et al., 2021). The global perspective on waste is shifting to see it as a resource that can be recovered, not an inevitable waste burden (International Solid Waste Association, 2024). Assessments of resource use further highlight the importance of decoupling economic growth from material use and environmental harm (Bruyninckx et al., 2024). The practical approaches for recovering compost, nutrients and energy from the organic wastes are aerobic and anaerobic digestion, while at the same time minimising waste disposal (Wainaina et al., 2020). However, policy gaps and differential entrepreneurial capacity remain to affect the uptake of circular economy in Sub-Saharan Africa (Tewodros, 2024). To valorise effectively, the source separation, appropriate transportation, pretreatment (Zhang et al., 2022), and design of the recovery system should be carried out first.

The phenomenon of waste composition influencing the treatment results is further illustrated in national experiences in China (Zhu et al., 2021), where the economic conditions, urbanization and technology also play a role in influencing the treatment results. Therefore, the purpose of this research is to assess the efficiency of recycling and material recovery process in waste management systems around the world. It includes the variability at country level in waste generation, composition, waste recycling, composting, incineration, open dumping and reliance on disposal.

The goals are to estimate the amount of recoverable waste, to analyze the economic performance and regional differences, to consider the correlation of recycling and system parameters, and to understand what key factors could facilitate or hinder sustainable waste-to-value transitions.

2. METHODOLOGY

2.1 Research Design and Data Selection

The research design for this study was quantitative and cross-sectional with a secondary data approach from Kaggle for waste management data from around the world. The country as the main unit of analysis was selected because the country level information on the amount of municipal solid waste generated, waste composition, recycling performance, treatment methods and disposal for waste could be consistently compared across regions and income groups. The data included information on 217 countries and territories (Arman et al., 2019). The primary variables included population, gross domestic product, income category, region, total municipal solid waste generation, waste composition, waste collection coverage, recycling, composting, incineration, landfill, open dumping, and waste management governance. Observations were included based on the availability of appropriate variables. As a result, the sample sizes were different across different analyses.

2.2 Variables and Indicator Development

Recycling efficiency (percentage of municipal solid waste sent to recycling) was the primary dependent variable. Biological recovery pathways included composting, anaerobic digestion, and thermal treatment pathways included incineration. Disposal pathways were defined as controlled landfill, sanitary landfill, unspecified landfill and open dumping. The primary waste that was recovered was paper and cardboard, plastic, glass, metal, food and organic waste, and yard waste. Dry material recovery potential was estimated to be as follows:

Dry Recovery Potential=Paper+Plastic+Glass+Metal

Biological recovery potential was calculated as:

Biological Recovery Potential=Food and Organic Waste+Yard Waste

Observed resource recovery was estimated using:

Observed Recovery=Recycling+Composting+Anaerobic Digestion

The difference between the potentially recoverable materials and the percentage recovered was calculated to determine the waste-to-value recovery gap:

Recovery Gap=Dry Recovery Potential+Biological Recovery Potential−Observed Recovery

A higher gap indicated more material of the recyclable/biodegradable was not being used. The percentages of waste sent to landfill and open dumping were added together to determine the percentage of waste that is disposed of in a dependent manner. The per capita generation of waste was obtained by dividing the amount of annual municipal solid waste generated by the number of people in the population. Explanatory variables included region, income group, gross domestic product, population, percentage of waste collected, legislation, and enforcement mechanisms, as well as waste information systems.

2.3 Data Preparation and Quality Control

Data were examined for consistency, completeness, measurement units and coding format. All country names, regional groups and income classifications were standardized for analysis. Some numerical data has been standardized and some duplicate and partially completed records have been reviewed. The percentages of waste composition and waste treatment were checked for negative values or values above 100%. Treatment pathway totals were also evaluated for unusual or implausible observations. Values that were not obviously invalid were included in the analysis, and values that were obviously invalid were retained but not included in the analysis. Handling missing observations was conducted by complete-case procedures specific to the analyses. Variables with very low coverage such as anaerobic digestion were only used for limited description of the results and were not considered in the main regression model. All Derived Indicators were derived only if all variables required for the indicator were available. Where necessary, highly skewed variables such as population, gross domestic product and generation of total waste were logarithmically transformed.

2.4 Statistical Analysis

Waste generation, material composition, recycling, composting, incineration, landfill use, open dumping and gap in recovery were presented in terms of descriptive statistics (mean, median, stand deviation, minimum, maximum, frequency and percentage). Regional and income group comparisons were carried out to find out the differences in recycling efficiency, material recovery potential and dependency on disposal. Variations between groups were presented using comparative bar charts and boxplots. Pearson correlation was used if the variables were normally distributed and Spearman correlation was used if they were skewed. The statistics analyzed were the relationships among the recycling efficiency, recyclable material content, organic waste content, collection coverage, income level, waste production per capita and disposal dependency. Multiple linear regression analysis was carried out to find out predictors of recycling efficiency. The dependent variable was the recycling percentage, and independent variables consisted of the recovery potential, waste generation, collection coverage, income classification, regional classification, gross domestic product, and governance indicators. A separate regression model was used to test the factors affecting the waste-to-value recovery gap. The significance of the results obtained was evaluated at $p<0.05$ and results were presented in terms of regression coefficients, confidence intervals and adjusted R2values.

3. RESULTS

3.1 Global Waste Generation, Composition, and Treatment Profile

The country-level database comprised of 217 countries and territories. The availability of data also differed by indicator: 215 countries reported data on municipal solid waste generation, some 164-176 countries reported data on waste composition and some 124 countries reported data on waste recycling. Thus, sample sizes were used for analysis in a manner specific to each analysis, and missing observations were not regarded as zero. The average municipal solid waste generation per capita per day was 1.04 kg with significant differences between the countries. The highest portion of waste among all waste categories was food and organic waste (41.73%) and the aggregating proportion of paper, plastic, glass and metal (36.32%) showed a mean dry-material recovery potential. The mean reported recycling rate of 17.37% was higher than the composting rate of 8.14%. The smaller number of countries reporting the incineration pathway had an average of 28.43% of incineration. The total disposal dependency averaged 68.04% and open dumping was still significant (54.79%). Only 27 countries had a recovery gap, and it averaged 51.28 percentage points, meaning that a significant percentage of material was not recovered from these countries through recycling or biological treatment. Descriptive statistics of the global waste generation, composition, recovery and disposal indicators are presented in Table 1. It reflects that food and organic waste represents a major waste stream and that recycling and composting are far less than the overall recovery potential. Values of major indicators of waste composition and treatment are displayed in the global mean, in Figure 1. High disposal dependency and relatively low rates of recycling/composting are illustrated in the figure.

Table 1: Descriptive statistics of global waste generation, composition, recovery, and disposal indicators

Indicator	N	Mean	SD	Median	Minimum	Maximum
Waste generation (kg/person/day)	215	1.04	0.76	0.87	0.10	4.35
Food and organic waste (%)	176	41.73	17.90	43.20	3.10	87.60
Dry-material recovery potential (%)	164	36.32	14.35	35.08	6.20	75.90
Recycling (%)	124	17.37	15.23	13.66	0.00	67.00
Composting (%)	68	8.14	7.59	5.74	0.08	31.24

Incineration (%)	48	28.43	23.54	22.84	0.14	85.00
Open dumping (%)	68	54.79	30.86	57.70	4.00	100.00
Disposal dependency (%)	144	68.04	30.77	76.50	0.21	100.10
Waste-to-value recovery gap (%)	27	51.28	28.59	59.00	−11.89	90.95

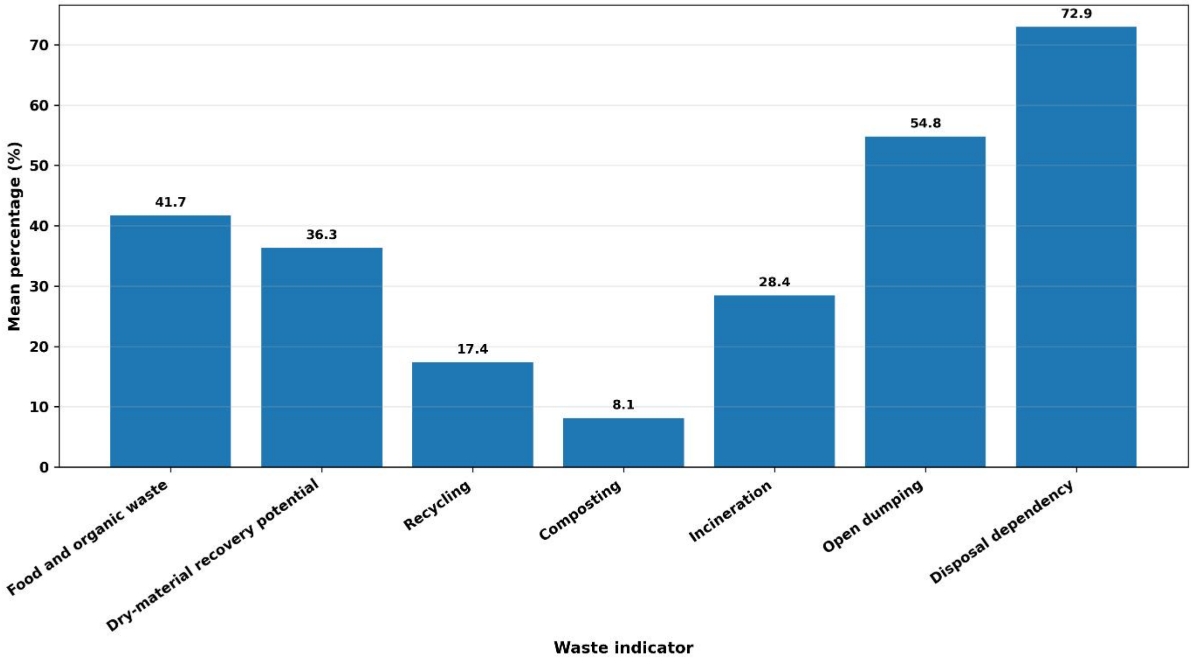

Figure 1: Global mean waste-composition and treatment indicators

3.2 Waste-to-Value Performance Across Income Groups

There were significant differences among income groups. The mean waste generation steadily rose from 0.45 kg per person per day in low-income countries to 1.69 kg per person per day in high-income countries. The mean recycling rates were also the highest in high-income country at 25.55%, which is around three times higher than the low-income country. The dry material recovery potential rose from 20.63% for low income countries to 44.76% for high income countries. On the other hand, the proportion of organic wastes in income decreased with the increase of income. Organic waste and food waste contributed over 50% of the waste stream in lower income and lower middle-income countries, whereas in high income countries, this figure was 32.82%. Disposal dependency was more than 80% in lower-middle and upper-middle income countries.

High income countries had lower disposal dependency (51.94%) but there was still a significant level of disposal. Countries with lower income had the highest rates of open dumping (71.89% for low income countries with observations). The differences in the waste-management indicators between the national income groups are presented in Table 2. Countries with high income demonstrate high organic-waste content, open dumping, and high potential for waste recovery from dry and recycling, while countries with low income demonstrate high potential for waste recovery from composting. The recycling rates by income group are presented in Figure 2. Generally, there is a positive relationship between income and recycling performance, with high-income countries having the largest range and highest median rate.

Table 2: Waste indicators by national income group

Income group	Waste generation (kg/person/day)	Recycling (%)	Composting (%)	Open dumping (%)	Disposal dependency (%)	Dry recovery potential (%)	Organic waste (%)
Low income	0.45	7.85	2.42	71.89	69.34	20.63	50.86
Lower-middle income	0.59	10.68	5.50	53.24	80.93	29.26	50.37
Upper-middle income	0.83	9.67	4.59	49.15	81.28	33.34	45.41
High income	1.69	25.55	11.07	52.24	51.94	44.76	32.82

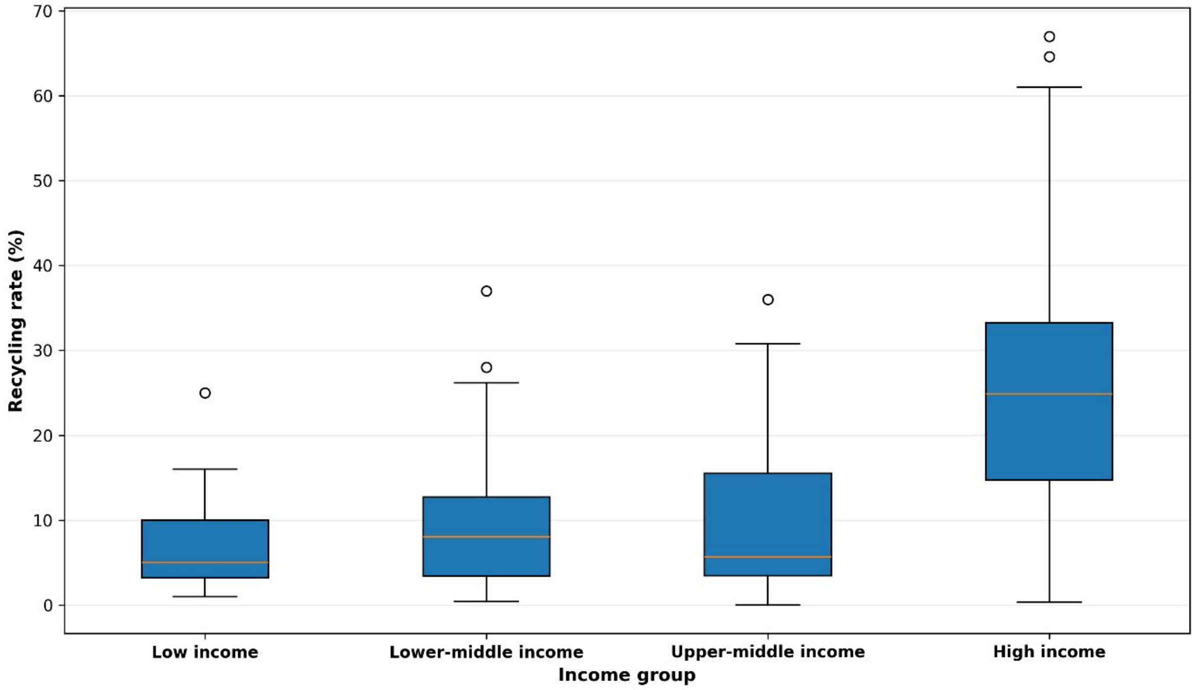

Figure 2: Distribution of recycling rates across income graph

3.3 Regional Variation in Material Recovery Pathways

The mean recycling rate in East Asia and the Pacific was the highest at 25.89%, with Europe and Central Asia coming in at 24.15%. The mean recycling rate in North America was 19.06%, while that in South Asia was the lowest, at 6.66%. The region with the highest composting rate is Europe and Central Asia (12.27%) with comparatively better biological recovery systems. The regional mean was also very low at 0.29% for composting in Latin America and the Caribbean. The Middle East and North Africa region had the highest level of disposal dependency with 87.19%, followed by Latin America and the Caribbean with 85.40%.

North America had the lowest mean dependency in disposal (45.71%) but there were only three country-level data points in this region. South Asia had the highest estimated recovery gap followed by the Middle East & North Africa and Latin America & the Caribbean. Regional recycling and other figures related to the recycling process are presented in Table 3. The recycling performance in East Asia and the Pacific is better, and the performance in Europe and Central Asia is also relatively high, but the performance in South Asia and the Middle East and North Africa is low. The correlation between recycling efficiency and dependence on disposal of countries is illustrated in Figure 3. The downward pattern reflects that the recycling rates tend to decrease over time as more and more of the waste is being sent to landfill and open dumping.

Table 3: Mean recovery and disposal indicators by global region

Region	Recycling (%)	Composting (%)	Incineration (%)	Open dumping (%)	Disposal dependency (%)	Recovery gap (%)
East Asia and Pacific	25.89	4.06	35.20	35.86	52.69	46.68
Europe and Central Asia	24.15	12.27	29.49	66.78	53.34	38.95
Latin America and Caribbean	7.97	0.29	40.22	36.43	85.40	69.02
Middle East and North Africa	8.82	5.78	1.59	64.38	87.19	70.50
North America	19.06	11.19	27.80	—	45.71	46.50
South Asia	6.66	5.93	6.00	70.67	77.40	75.54
Sub-Saharan Africa	9.12	4.77	—	72.06	77.56	—

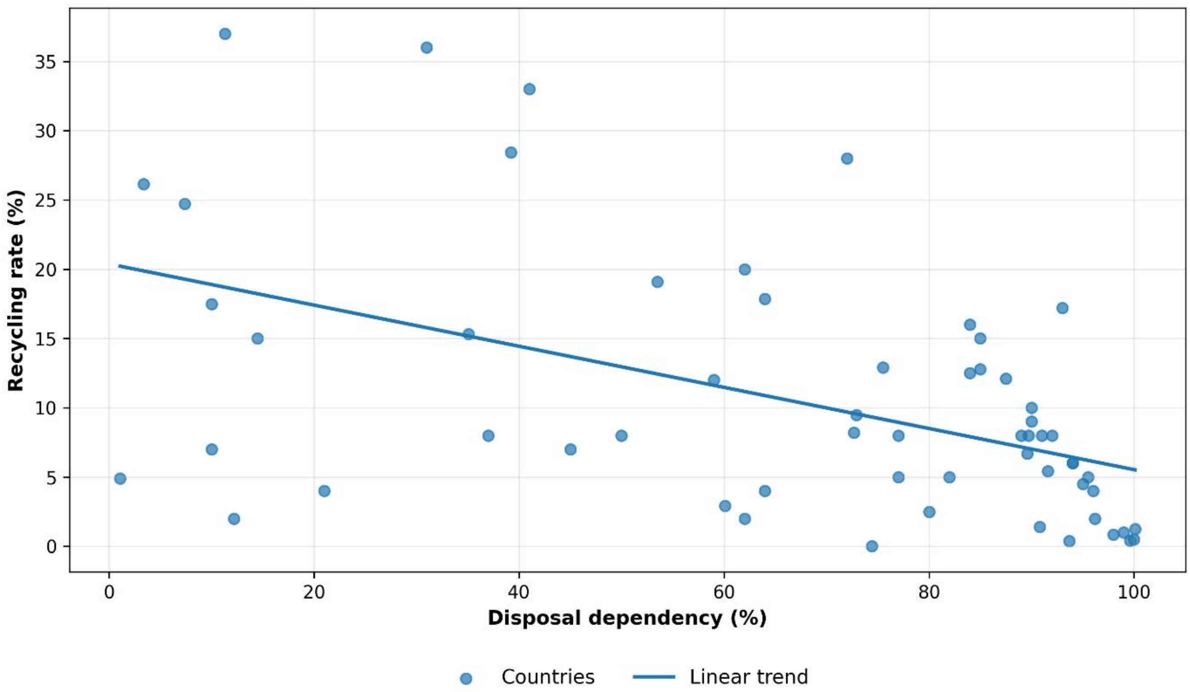

Figure 3: Regional recycling and disposal-dependency profiles

3.4 Relationships Between Recycling Efficiency and Waste-System Characteristics

The Spearman correlation analysis found that the recycling efficiency was positively correlated with dry-material recovery potential, waste generation per capita, and gross domestic product per capita. The highest positive correlation was found for recycling and GDP per capita ($\rho=0.537$, $p<0.001$). The percentage of food and organic waste was negatively correlated with recycling ($\rho=-0.385$, $p<0.001$). The inverse correlation between recycling efficiency and the dependence on disposal was the strongest ($\rho=-0.705$, $p<0.001$). This confirmed that countries that heavily depend on landfill and open dumping had much lower recycling rates compared to other countries. Collection coverage had a positive correlation with recycling but it was not statistically significant ($\rho=0.240$, $p=0.105$).

The result indicates that if waste collection is not combined with separation, recycling, and processing, then material recovery is less certain. The correlation and regression predictors related to the recycling efficiency are presented in Table

4. Disposal dependency is highest in absolute value of the negative relationship with recycling and is the only one of the variables that is statistically significant to the regression model. Regional recycling, composting, and dependency on disposal percentages are displayed in Figure 4. As seen in the figure, most of the regions are dominated by disposals, with a much smaller percentage of recycling and composting.

Table 4.: Correlations and regression predictors of recycling efficiency

Predictor	N	Spearman ρ	Correlation p-value	Standardized regression coefficient β	Regression p-value
Dry-material recovery potential	107	0.291	0.002	0.074	0.443
Food and organic waste	111	−0.385	<0.001	−0.076	0.427
Waste generation per capita	124	0.474	<0.001	0.099	0.270
Disposal dependency	101	−0.705	<0.001	−0.592	<0.001
Collection coverage	47	0.240	0.105	—	—
GDP per capita	112	0.537	<0.001	—	—

The multiple regression model included 92 countries with complete observations and was statistically significant, F487=22.38, $p<0.001$. The model accounted for 50.7% of the variation in recycling efficiency, and had an adjusted R^2 of 0.484. Statistically, only disposal dependency was an independent predictor. Every 1 standard deviation increase in disposal dependency corresponds to 0.592 standard deviations decrease in recycling efficiency.

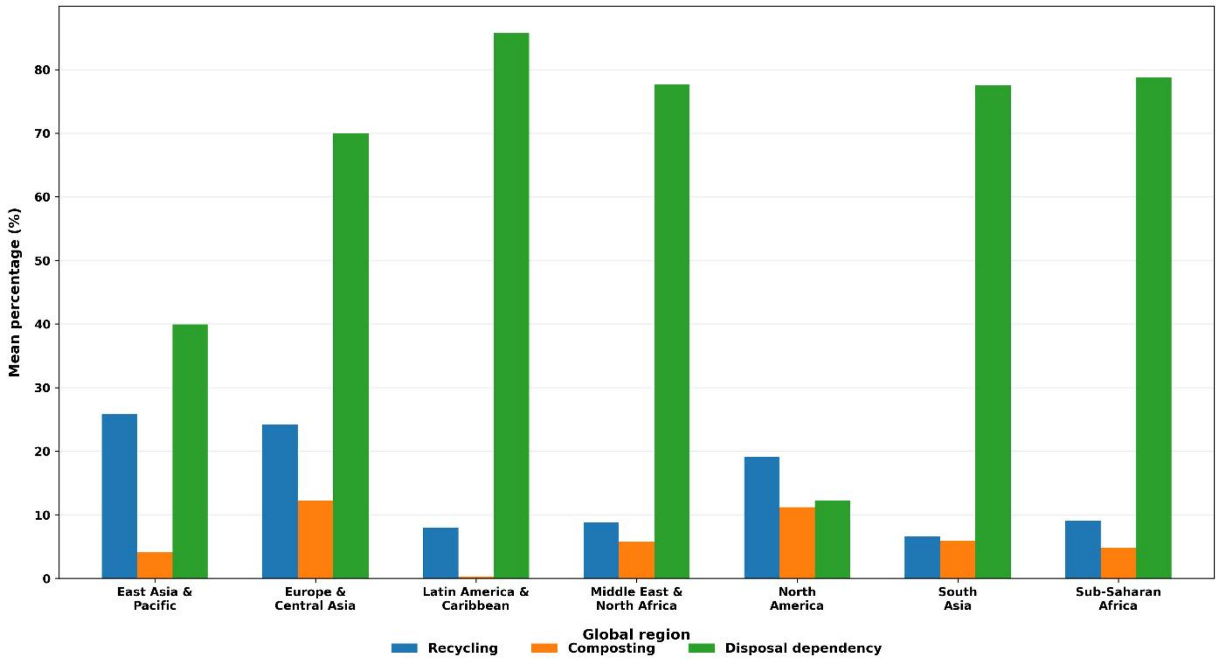

Figure 4: Relationship between recycling efficiency and disposal dependency

3.5 Overall Waste-to-Value System Performance

The results indicated that there is a significant discrepancy between available material for recovery and recovered material. The mean recycling rate was below 18% with dry recyclable materials accounting for over one-third of the average waste stream. Organic waste made up the highest proportion of waste, with a mean of 8.14% being composted, meaning there was a significant biological recovery potential in this waste stream that was not being used. The more developed countries had higher recycling performance and had a higher percentage of dry recyclable materials. But more waste was produced with this greater recovery. Lower income areas produce fewer wastes per capita, relied more on open dumping, and had fewer formal waste recycling and composting facilities. In total, dependency on disposal was the largest issue affecting recycling efficiency. Countries with a higher proportion of waste going through landfill or open dumping were less likely to channel waste to recycling and waste-to-value systems. The findings therefore show that there is a need to not only have waste recoverable, but also be able to move materials away from the disposal-oriented waste flows in any national waste system in order to achieve sustainable material recovery.

4. DISCUSSION

The results show that the world has a long way to go to the material-recovery potential that is contained within municipal solid waste. The highest average percentage was organic waste and a significant percentage was dry recyclable materials. While this resource base exists, the mean recycling and composting rates were still relatively low, meaning that there is still a pathway for potentially recovered resources to be transferred to landfill, back to open dumps, or to other destinations. The overall result confirms that waste composition is not the only condition that influences environmental sustainability in waste management, but also the capacity of infrastructure, governance, financing, and enforcement (Abubakar et al., 2022).
This significant difference between potential and actual dry-material recovery implies that recycling rates can be inadequate to fully assess circular performance. A nation can claim to recycle the amount of waste measured, but then have a much higher amount of waste that can be recovered and recycled. This concern is aligned with arguments that the recycling rate should be considered in combination with resource substitution, the avoidance of disposal and the quality of the material (Fellner & Lederer, 2020).
The present recovery gap indicator is thus a helpful complement to the indicator, as it indicates the share of the recyclable potential that remains unused. The results of the income group comparisons showed a strong structural split. The higher the income level, the more waste generated per capita, but the lower the dependency on waste disposal and the higher the recycling numbers. Low-income countries had lower per capita waste generation, but higher recycling rates and higher open dumping rates. The differences are attributed to variations in collection systems, source segregation, treatment capacity, regulatory ability and secondary-material markets. The findings in this study are consistent with the worldwide assessments of waste-management and valorization pathways (Kafle et al., 2025). The results further underscore evidence that transitions towards a circular economy need to be city- and region-specific, rather than one-size-fits-all technologic fixes (OECD, 2020).
The results by region indicated that Europe and Central Asia, as well as East Asia and the Pacific, had comparatively better recycling performance while South Asia had the lowest recycling level. There is high dependency on disposal in the Middle East and North Africa and Latin America and the Caribbean, suggesting that landfilling continues to be the predominant management route in some geographic areas. This regional variation mirrors the bibliometric and policy evidence of the geographical disparities of waste-management innovation and research capacity (Ndou & Rampedi, 2022). It also captures

variations in material markets, formal-sector involvement and regulatory enforcement. There is a negative relationship between the share of the organic waste and recycling, indicating that the conventional recycling systems may not be well suited for areas with a high percentage of biodegradable waste in municipal waste streams.

In an organic-rich system biological recovery pathways must be used, not dry materials recovery paths. Biodegradable waste can be transformed into soil amendments, energy, and other valuable products through composting, anaerobic digestion, and integrated nutrient recovery processes (Wainaina et al., 2020). Depending on the organic fraction, the recovery of bioenergy can also help to minimize uncontrolled disposal (Nanda & Berruti, 2021). But biological treatment is still reliant on proper segregation as contamination causes loss in process efficiency and product quality. There is a positive relationship between GDP per capita and waste generation per person, suggesting that higher economic capability could facilitate the development of formal waste collection, sorting, treatment facilities and the market. However, circularity is not a given in economic development. More affluent systems could also produce more packaging and plastics waste, putting more strain on the recovery process. Economic instruments, producer responsibility and international policy coordination are thus key issues in global plastic-governance research (Barrowclough & Birkbeck, 2022). Similar future plastic-policy scenarios indicate that more stringent measures are needed to address leakage into the environment (Sonke et al., 2025).

The greatest statistical result was the large negative correlation that was obtained between disposal dependency and recycling. In the multivariable model, only disposal dependency was significant, suggesting that the use of landfills and open dumps directly limits recovery performance. When segregation, recycling, composting and waste-to-energy are not economically competitive or are institutionally dominant, they are less appealing investment options. Multiple material components can be recovered to improve environmental and economic outcomes prior to final disposal through integrated treatment strategies (Liang et al., 2022). Therefore, source separation and pretreatment are crucial to recover more and better value from materials (Zhang et al., 2022).

Overall, the results indicate that a shift from the disposal oriented waste management to the coordinated waste recovery systems is needed to establish sustainable waste-to-value systems. A combination of recycling with biological treatment, energy recovery, participation of stakeholders and policy instruments is necessary. This integration can help to promote the use of resources more efficiently, lower environmental pollution and help to meet sustainable-development goals. The results also show that waste interventions need to be tailored to the waste content, economic capability and institutional context of the region rather than to a standard recovery model globally.

5. CONCLUSION

The recycling performance and material-recovery streams in the waste-management systems in each of the countries for the world were assessed through country-level indicators of waste generation and composition, treatment and disposal. The results indicated that there is significant potential for recycling from MSW, especially for organic materials and dry recyclables. The percentage of recycling and composting, however, was still significantly lower than the percentage of material which could be recovered, indicating material available but not being recovered. Significant disparities were found among income groups and area. The recycling percentage was higher and dependency on open dumping was lower in high-income countries, while the opposite was seen in low-income countries, which had a higher dependency on open dumping despite a lower waste production per capita. The regional performance also showed significant differences, depending on the infrastructure, the government, financing, the source separation and the markets for secondary materials. The statistical analysis also showed that dependency on disposal was the most negative factor affecting recycling performance. This means that the more landfilled and open dumped systems are the less likely they are to build effective systems for recovery. These findings indicate that enhancing waste-to-value performance benefits are not solely dependent on the recycling rate. Countries need to implement integrated systems, which involve source separation as well as dry-material recycling, composting, anaerobic digestion, energy recovery, and controlled disposal of residues. Policy measures should also enhance the institutional capacity, coordination, data quality, market incentives and investments in recovery infrastructure. The shift towards sustainable waste-to-value systems relies on decreasing the dependency on waste disposal, and aligning recovery technologies to the composition of waste, and the economic and market conditions. Such a coordinated circular economy strategy can help to enhance the efficiency of resources use, lower the amount of pollution, save raw materials and promote more resilient and sustainable waste-management systems globally.

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