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Assessment of Waste-to-Value Potential in Municipal Solid Waste: Composition-Based Recycling, Composting, and Energy Recovery Analysis

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Abstract

The potential of municipal solid waste (MSW) as a recoverable stream of resources is on the rise in preference to being a disposal burden, but combined evaluations combining recycling, composting, and energy recovery potential are limited. This study evaluates the waste-to-value potential of MSW using a composition-based analytical framework applied to 77 regional composition profiles spanning 1999–2022. Material fractions were harmonized into major categories and normalized to ensure consistency. The recyclable fraction (paper, plastics, glass, and metals) and compostable fraction (food, yard waste, and other organics) were combined to estimate total diversion potential, while energy recovery potential was calculated using a weighted lower heating value approach for profiles with sufficient combustible-fraction detail (n = 57). A composite Waste-to-Value (WTV) Index was developed to integrate diversion efficiency and normalized energy performance. The results indicate a mean total diversion potential of 81.04%, with a residual fraction of 18.96%. Paper (25.65%), food waste (15.23%), and plastics (14.56%) were the dominant components of the waste stream. Mean energy recovery potential averaged 10.80 MJ/kg (SD 1.54), with several regions combining high diversion rates and elevated calorific values. Regional variability was more pronounced than temporal change across the study period. The composition-based indicators reveal substantial theoretical recovery capacity within MSW streams and highlight the importance of integrated strategies that combine recycling, composting, and energy recovery to support sustainable waste management transitions.

Keywords: *municipal solid waste, recycling, waste-to-energy, resource recovery, sustainable waste management*

1. INTRODUCTION

The production of municipal solid waste (MSW) has grown significantly in the last several decades due to the dramatic urbanization, the growth of population, and the shift in consumption behaviors. The increasing amount of waste in the world has resulted in increased environmental strain, leading to the problem of greenhouse gases, land use, and environmental degradation (Chen et al., 2020). Although technology has advanced waste management, landfill is a prevalent waste disposal route in most areas that is usually linked to prolonged environmental risks and opportunities cost of resources (Nanda and Berruti, 2021). These difficulties have led to the shift to the framework of waste management with resources focus that is more directed to recovery than disposal. Sustainable MSW management is placing an emphasis on the principles of the circular economy, in which waste flows are viewed as byproducts instead of the residual burdens (Bello et al., 2022). In this paradigm, material recycling, as well as biological stabilization procedures, is important to minimize landfill dependency. Biological methods of dealing with organic fractions, such as composting and other technologies, should be used to reduce methane formation and to recycle nutrients (Amalia et al., 2021). At the same time, combustible fractions in MSW are a potential source of energy, and they can be used to create waste-to-energy (WtE) systems (Kaur et al., 2023). The technological developments opened up the list of MSW valorization options, such as thermal, mechanical-biological, and incorporated recovery (Khan et al., 2022). The advanced methods are expected to improve the recovery efficiency and economic viability, as well as environmental performance (Ghumra et al., 2022). The correct estimation of energy potential has gained a special role because incineration and pyrolysis systems are largely dependent on the calorific value of the fed waste (Ganesapillai et al., 2023). The development of new analytical tools has also enhanced the ability to predict heating values on the basis of composition information, enhancing the connection between waste characterization and energy system development (Lim et al., 2024).

There is a significant amount of literature that investigates single elements of MSW management systems. Such approaches as landfilling technologies and their perception of the environment (Nanda and Berruti, 2021) and sustainable management strategies aimed at optimization of systems in the long run (Bello et al., 2022) have been reviewed. In the same way, other researchers have investigated the topic of MSW as a renewable source of energy, including the combustion, gasification, and similar technologies (Kaur et al., 2023). The bigger picture of global waste production trends reveals the necessity of switching to the systems of recovery (Chen et al., 2020). Technological and biochemical perspectives have also been explored as far as the valorization of MSW is concerned. Waste-derived fuels have been identified by thermogravimetric analyses and their characteristics of combustion evaluated (Gerassimidou et al., 2020). The analysis of the latest recovery technologies underscores the importance of integrated processing methods in the extraction of maximum value in the consumption of heterogeneous waste streams (Khan et al., 2022). On the same note, the significance of harmonizing recovery plans with material composition properties can be highlighted by technological syntheses of waste-to-value pathways (Ghumra et al., 2022). There is an increasing interest in organic waste management, especially the composting technologies and optimization of biological treatment (Amalia et al., 2021). Simultaneously, waste-to-energy system modelling techniques are also moving towards the idea of composition-based approximations to enhance waste management efficiency and stability in their operations (Ganesapillai et al., 2023). High-level calculation methods have contributed to the estimation of calorific value of waste fractions, which serves to prove the applicability of the composition data to the energy recovery planning (Lim et al., 2024). Also, the regional difference in waste composition is noted by policy-crafted reviews and its consequences on recovery plans (Meena et al., 2023).

Although the literature has performed a thorough assessment of waste management technologies and recovery processes of individual waste management, there has been little integrated assessment of material diversion potential and energy recovery potential. The majority of literature works are devoted to the recycling performance, biological stabilization, or thermochemical conversion separately. There are not many analyses that involve recyclable fractions and compostable ones along with the theoretical calorific value in the same framework in which cross-regional comparison was possible. In addition, the limited synthesis of multi-year regional composition data that would be needed to determine combined waste-to-value capacity with time was missing, even though composition-based modelling strategies have been created to determine heating values and fuel properties (Gerassimidou et al., 2020). The policy and infrastructural planning would fail to capture the interaction between the material recovery efficiency and the combustible energy potential without integrated indicators. A systematic composition-based appraisal is consequently needed to measure the hypothetical recovery capacity that is enshrined in MSW streams.

This research aims to evaluate the waste-to-value character of municipal solid waste that has been conducted through an analytical method based on the composition. In particular, the research measures recyclable and compostable fractions to obtain an estimate of potential diversion, determines the energy recovery potential given the composition of combustible material, analyzes the temporal variability in these measures, and constructs a composite Waste-to-Value Index, which is a composite of material and energy recovery performance.

2. METHODOLOGY

2.1 Study Design and Analytical Framework

This study used a composition-based analysis framework to measure the theoretical value of waste-to-value at municipal solid waste (MSW) systems. The methodological framework incorporates three recovery pathways, which include: material recycling, biological treatment and thermochemical energy conversion. The records of MSW composition in regions were considered independent units of analysis, and they could be cross-sectionally and temporally compared across jurisdictions. The analytical process was to estimate three key indicators of recovery: recyclable fraction, compostable fraction and the energy recovery potential. These indicators were then combined into a composite Waste-to-Value (WTV) Index to aid regional evaluation.

2.2 Data Source

The dataset of MSW composition records used in the presented study was obtained using the publicly available dataset that was used to implement the county-scale modeling work by Grassel et al. (2025). The records collected cover 1999-2022 and reflect 77 regional MSW composition profiles. All the profiles will show disaggregated material fractions, such as paper products, plastics, glass, metals, organics, construction and demolition materials, household hazardous waste, and miscellaneous residual components. The profile of each regional composition was considered to be an independent observation. In cases where there were many regional records in one-year, annual statistics were calculated as the arithmetic means of regional values.

2.3 Data Harmonization and Aggregation

In order to compare the results across regions and years, material subcategories were merged together into standard major groups in line with the waste management and recovery literature. The combined groups were the paper, plastics, glass, metals, food waste, yard waste, other organics, wood, construction and demolition waste (not including wood), household hazardous waste, and other residual materials. In the case of all regional profiles, fractional components were checked to add up to unity with the rounding tolerance. In the case of minor inconsistencies, proportional normalization was used. This is because records that did not contain enough material to be aggregated were not included in energy calculations, but were included in the diversion analysis when deemed good.

2.4 Estimation of Material Recovery Potential

2.4.1 Recyclable Fraction

Recyclable fraction was established as the total of the materials that can usually be recycled through the existing recycling systems, which are paper, plastics, glass, and metals. For each regional observation, the recyclable fraction was calculated as:

$$R_i = P_i + Pl_i + G_i + M_i \tag{1}$$

where R_i represents the recyclable share for the region i, and P_i, Pl_i, G_i, and M_i denote the fractional contributions of paper, plastics, glass, and metals, respectively.

2.4.2 Compostable Fraction

The compostable fraction contained the biodegradable material that can be used in a biological treatment process like composting or anaerobic digestion. This fraction was calculated as:

$$C_i = F_i + Y_i + O_i \tag{2}$$

where C_i represents the compostable share for the region i, and F_i, Y_i, and O_i correspond to food waste, yard waste, and other organic materials.

2.4.3 Total Diversion Potential

Total diversion potential was defined as the combined recyclable and compostable fractions:

$$D_i = R_i + C_i \tag{3}$$

where D_i represents the theoretical diversion potential for the region i. The residual fraction was derived as:

$$Res_i = 1 - D_i \tag{4}$$

The residual portion is the material which cannot be retrieved under conventional recycling or composting on assumptions of composition.

2.5 Estimation of Energy Recovery Potential

The potential of energy recovery that can be developed in the regional observations that had enough detail of combustible material was estimated. The lower heating value (LHV) approach was used, in which the proportional contribution of each combustible material to the total waste stream was used to weight the calorific value of that material. Energy potential was calculated as:

$$E_i = \sum_{j=1}^{n} (w_{ij} \times LHV_j) \tag{5}$$

where E_i is the energy recovery potential (MJ/kg) for the region i, w_{ij} represents the fractional share of the combustible component j, and LHV_j denotes its corresponding lower heating value.

Glass and metals, along with inert fractions, were not included in this calculation as they are non-combustible. Energy was put in megajoules per kilogram (MJ/kg). Unit conversions were used (where necessary) to convert energy in megawatt-hours per ton (MWh/ton). The potential of energy recovery could be estimated in 57 observations of the region.

2.6 Development of the Composite Waste-to-Value Index

To enable integrated comparison of diversion efficiency and calorific performance, a composite Waste-to-Value (WTV) Index was constructed for observations containing both D_i and E_i. Energy values were normalized using min–max scaling:

$$E_i^* = \frac{E_i - E_{min}}{E_{max} - E_{min}} \tag{6}$$

The composite index was then calculated as:

$$WTV_i = \frac{1}{2} D_i + \frac{1}{2} E_i^* \tag{7}$$

where WTV_i ranges from 0 to 1. Equal weighting was applied to reflect balanced consideration of material recovery efficiency and energy recovery potential.

2.7 Statistical Analysis

All of the material categories and recovery indicators (mean, standard deviation, minimum, median and maximum) were calculated as descriptive statistics. Average annual values were estimated in cases where there were several observations in the same year in different regions to measure change with time.

3. RESULTS

3.1 Dataset Characteristics and Temporal Coverage

After data cleaning and normalization, 77 regional Municipal solid waste (MSW) composition profiles were left to be analyzed. These profiles are between 1999 and 2022, with disproportionate annual representation. The largest number of observations at the regional level was noted in 2005 (n = 13), then 2020 (n = 11) and 2021 (n = 8), with a number of years being subject to one regional composition profile. Mean total diversion potential (recyclable and compostable fractions) differed between years, with the lowest at 70.9% (both in 2002 and 2014) and the highest at 91.1% (2011). Annual mean values showed a higher variation in years with low regional representation (Table 1; Figure 1).

Table 1: Annual distribution of regional observations and mean total diversion potential

Year	Regional observations (n)	Mean total diversion potential (%)
1999	1	86.1
2001	6	85.2
2002	5	70.9
2003	1	76.1
2005	13	85.3
2006	1	80.2
2008	1	74.5
2010	2	84.7
2011	2	91.1
2014	5	70.9
2015	7	78.5
2016	3	82.2
2017	3	85.8
2018	3	82.2
2019	4	77.8
2020	11	81.1

2021	8	83.0
2022	1	75.5

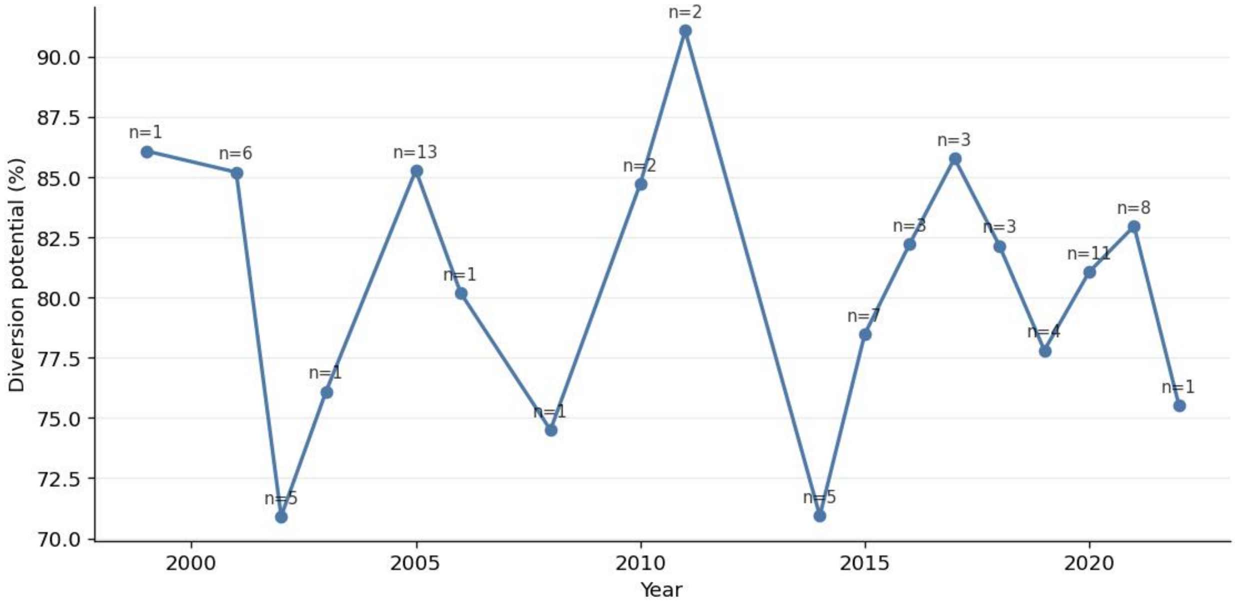

Figure 1: Annual Mean Total Diversion Potential of Municipal Solid Waste (1999–2022)

3.2 Major Municipal Solid Waste Composition

The waste stream included mostly paper waste, food waste and plastics across the 77 normalized regional MSW composition profiles (Table 2; Figure 2). The greatest average value (25.65%), food waste (15.23%), and plastics (14.56%) represented the largest percentage of paper, food waste, and plastics, respectively. Construction and demolition (C&D) waste, other than the wood, had a figure of 10.33 and yard waste had 8.33. Intermediate fractions were made up of metals (5.87%), other organics (5.90%), and wood (5.13%). Other lower categories were textiles (4.17%), glass (2.86%) and household hazardous waste (0.83%). There was a significant interregional difference, especially in paper, C&D waste and yard waste fractions.

Table 2: Mean composition of major MSW categories (%, n = 77).

Waste category	Mean (%)	SD	Min	Median	Max
Paper	25.65	7.89	7.54	25.16	41.56
Plastics	14.56	3.47	8.40	14.43	23.89
Food waste	15.23	3.75	7.09	14.20	23.95
Yard waste	8.33	4.05	1.50	7.17	19.88
C&D waste (excl. wood)	10.33	5.75	3.41	8.99	29.32
Metals	5.87	1.59	2.94	5.65	10.80
Other organics	5.90	2.95	1.46	4.90	13.94
Wood	5.13	4.05	0.20	3.58	19.00
Textiles	4.17	1.37	1.59	3.99	9.19
Glass	2.86	0.92	1.34	2.77	5.10
Household hazardous waste	0.83	0.96	0.00	0.50	5.09
Other	5.78	4.37	0.78	5.29	26.54

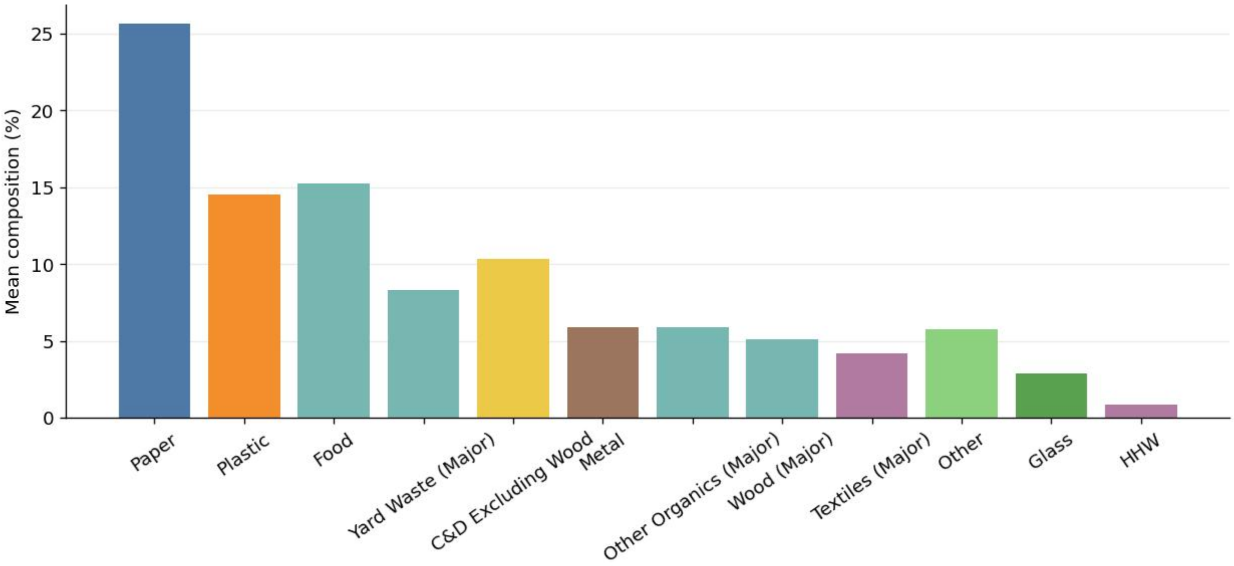

Figure 2: Mean Major-Category Composition of Municipal Solid Waste (n = 77)

3.3 Waste-to-Value Potential

The total recyclable percentage according to composition grouping was 46.94 on average, and the compostable percentage was 34.09 on average, which gave the diversion potential of a total of 81.04 (Table 3). The rest of the residual fraction was 18.96 on average. These data show that, based on the assumptions of composition-based recovery, about four-fifths of the municipal waste stream could theoretically be recovered by taking the recycling and composting routes. Figure 3 shows the proportional contribution of recyclable, compostable and residual fractions.

Table 3: Overall waste-to-value potential (n = 77).

Component	Mean (%)	SD	Min	Median	Max
Recyclable fraction	46.94	10.18	23.21	46.11	67.80
Compostable fraction	34.09	7.09	19.20	34.94	48.40
Total diversion potential	81.04	7.33	57.39	82.31	95.39
Residual fraction	18.96	7.33	4.61	17.69	42.61

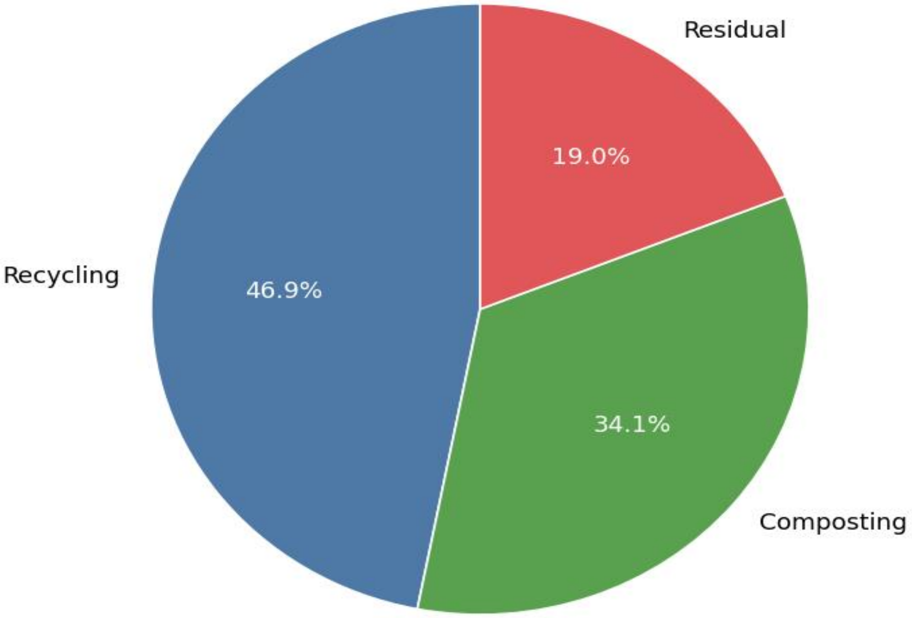

Figure 3: Overall Waste-to-Value Distribution: Recyclable, Compostable, and Residual Fractions (Mean Values)

3.4 Temporal Trends in Diversion and Energy Recovery

The overall diversion potential annual mean showed variability during the study period without any indication of a steady rising or falling trend (Table 4; Figure 4). The average values of the diversion were higher in 2011 (91.1%) and 2017 (85.8%), and relatively low in 2002 and 2014 (70.9%). The interannual variation which was observed must be due to variation in regional composition profiles and the annual sample sizes and not due to a linear temporal change. Potential energy recovery based on 57 regional composition profiles with detailed combustible-fraction data was used to determine that the energy recovery of 10.80 MJ/kg (SD 1.54) was on average across the study period. Table 4 depicts that the average energy of the years in which a full year of calorific estimates were available was found to range between 8.22 MJ/kg 2002) and 12.56 MJ/kg (2005). Over the past few years, as a result of the availability of calorific data (2017-2022), the mean energy potential was relatively constant (around 10 MJ/kg), and calorific characteristics of the combustible fraction remained relatively constant (Figure 4).

Table 4: Annual mean diversion and energy recovery potential.

Year	Regional observations (n)	Mean diversion (%)	Mean energy potential (MJ/kg)
1999	1	86.1	9.37
2001	6	85.2	10.51
2002	5	70.9	8.22
2003	1	76.1	9.20
2005	13	85.3	12.56
2014	5	70.9	9.74
2015	7	78.5	9.41
2016	3	82.2	10.41
2017	3	85.8	11.15
2018	3	82.2	9.97
2019	4	77.8	11.30
2020	11	81.1	10.89
2021	8	83.0	9.42
2022	1	75.5	12.02

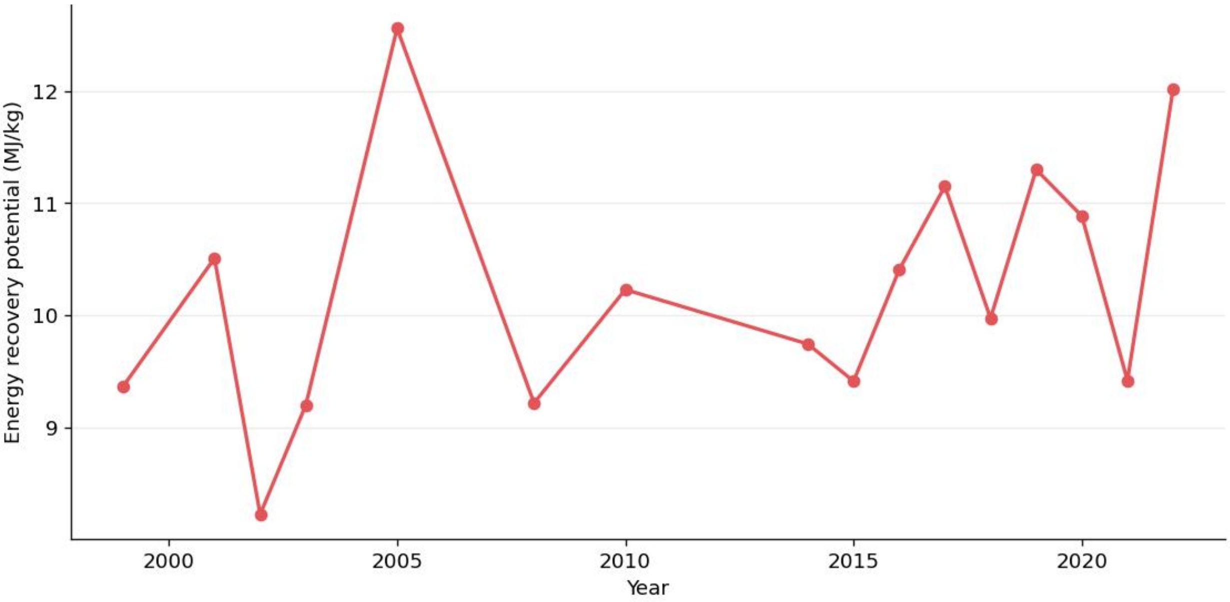

Figure 4: Annual Mean Energy Recovery Potential of Municipal Solid Waste (MJ/kg)

3.5 Regional Performance Based on Combined Waste-to-Value Index

A composite Waste-to-Value (WTV) Index was created to compare the performance of integrated recovery, and evaluate the total diversion potential in conjunction with energy recovery potential in the regional profile of composition, in conjunction with the entire calorific information. As indicated in

Table 5, top performing regions were largely experienced in the year 2005. Coastal Georgia had the highest index value (0.9939), next was Northeast Georgia (0.9848), and lastly, the Central Savannah River Area had the index value of 0.9552. These areas were characterized by large diversion rates (more than 87) and high calorific values (more than 12.8 MJ/kg), which means that they were highly suitable for integrated waste-to-value approaches. Areas having low values of the composite index were those that had a relatively low diversion potential and/or a low energy recovery potential. Table 5 indicates the ranking of the most successful regions as shown in Figure 5.

Table 5: Top regions based on the combined Waste-to-Value Index.

Rank	**Region**	**Year**	**Total diversion (%)**	**Energy potential (MJ/kg)**	**WTV Index**
1	Coastal Georgia	2005	89.0	13.14	0.9939
2	Northeast Georgia	2005	88.8	13.07	0.9848
3	Central Savannah River Area	2005	87.2	13.02	0.9552
4	Chattahoochee Flint	2005	87.0	12.96	0.9466
5	Atlanta Regional Commission	2005	87.1	12.83	0.9374

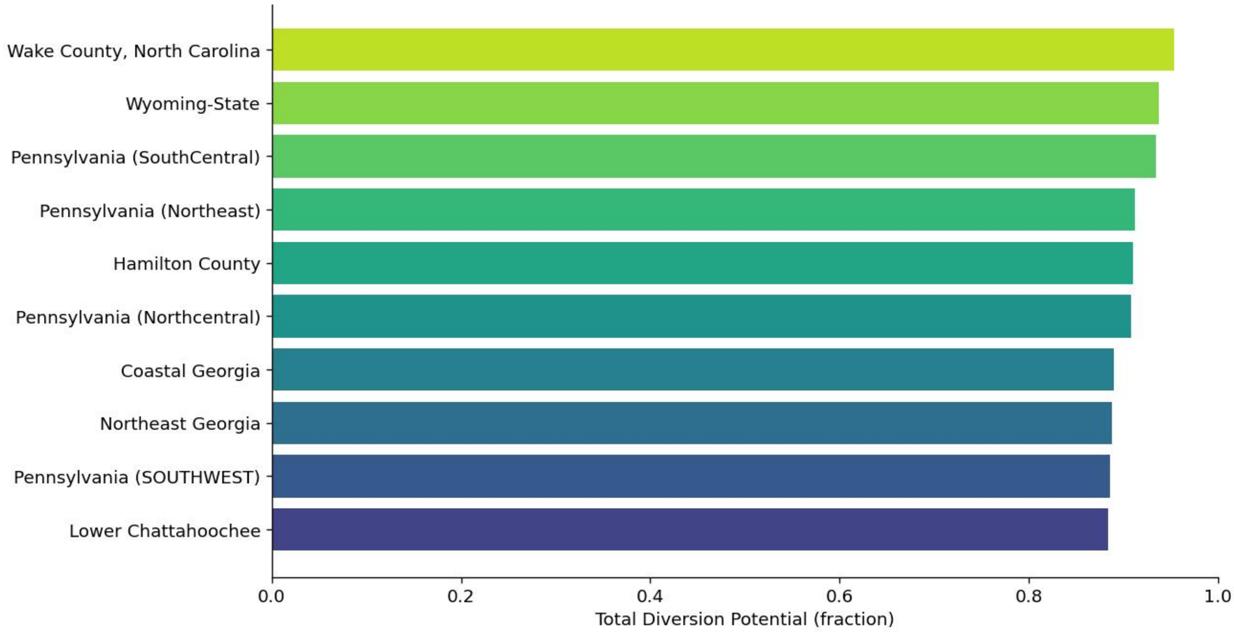

Figure 5: Top-Performing Regions Based on Combined Waste-to-Value Index

4. DISCUSSION

The composition-based analysis performed in the study shows that municipal solid waste (MSW) has significant theoretical recovery potential when considered using diversion and energy indicators in a composite way. The summed-up recyclable and compostable fractions constituted more than four out of five total masses on average, which implies that a substantial percentage of the garbage stream can be structurally lethal to recovery routes in optimal management circumstances. The fact that the paper, food waste, and plastics are the major constituents underscores their main influence on the determination of the efficiency of diversion. In particular, organic fractions are a significant prospect of biological stabilization and material recirculation, whereas recyclable dry fractions have a direct effect on material recovery performance. Combustible components have an energy recovery potential of approximately 10.8 MJ/kg, averaged across all profiles which had sufficient calorific detail. This value indicates the average yet significant embedded energy content in the residual stream. Even though this is not an actual operational output, it means that the thermochemical treatment can be done with post-diversion residues of combustibles under the right infrastructure conditions. The unsteady monotonic change in time in the indicators of diversion and energy curves also indicated that interannual change can be better attributed to regional heterogeneity and distribution of samples than systematic structural change. The composite Waste-to-Value (WTV) Index also indicates that the optimal regional performance is due to the equilibrium between the potential of diversion and calorific value, which confirms the significance of the integrated evaluation as opposed to the single evaluation of pathways. This significant diversion possibility, which was found in this analysis, aligns with waste value potential frameworks, which quantify recoverable proportions as a planning input towards peri-urban systems (Ekanthalu et al., 2020). The existence of methodological progress in the computation of recycling value out of standardized composition analysis also provides further support to the applicability of composition-based measures in the estimation of embedded recovery capacity (Hemali et al., 2024). The energy recovery estimates can be compared with the current developments in the waste-to-energy technologies that focus on enhancing the efficiency and environmental performance of conversion due to the enhanced feedstock characterization (Abedin et al., 2025). Extensive evaluations of energy recovery systems based on sustainability also highlight the significance of the association of waste content and technologies to reduce environmental effects (Kumar et al., 2025).

The analysis conducted in spatial planning shows that the viability of waste-to-value systems lies not just in the material composition but also in the optimal location of a facility and the logistical connection of the latter, which means that compositional potential should be viewed in more comprehensive concepts of geographic planning (Tazin et al., 2024). In addition to MSW, the literature of valorization in industry-specific environments demonstrates that the streams of residual biomass may be converted into high-value products when the material properties are appropriately matched with the conversion routes (Ratto et al., 2025). The new scholarship on the circular economy also emphasizes the increased use of intelligent systems, such as AI-based sorting and robots, as part of improving the fraction purity and decreasing residual disposition (Heikkilä et al., 2023). The overall intelligent waste management strategies also focus on coordinated resource optimization of numerous waste streams (Sharma et al., 2023). Besides, the cross-sector pathways of valorization such as the application of waste-derived products in the wastewater treatment strategies, explain the widening scope of waste-to-value integration (El-Emam, 2024). All these studies taken together support the idea of the conceptual validity of the interconnection of material and energy recovery into one analytical framework.

These results have three main implications for the development of strategies of waste-to-value. First, the large theoretical diversion fraction indicates that enhancing the system of paper, plastics, and organics separation is also a significant lever in improving the reduction of residual disposal. Second, the visualized calorific potential suggests that energy recovery can be used as an add-on to the non-recyclable combustible residues, assuming that environmental protection and relevant technologies are established. Third, the WTV Index provides a compact comparative measure that applies the efficiency of the diversion and calorific performance, which could help the decision-makers define areas where the integrated recovery investments can bring greater systemic value.

The research is based on composition-based metrics and hence, reflects recovery potential as opposed to operational efficiency. Practical diversion and energy production are dependent on the efficiency of the collection, control of contamination, design of infrastructure and the market environment. Uneven annual representation impacts the temporal variability and prevents effective inferences concerning the structural trends on a long-term basis. The energy recovery could only be calculated on profiles with enough detail of the combustible-fraction.

The future studies ought to combine compositional analysis with spatial planning models, include socio-economic and policy variables, and balance the calorific estimates with measured data on the operations. The growth of multi-year records of composition and the association of them with technology-specific efficiency parameters would increase the translation of theoretical potential into practicable waste-to-value plans further.

5. CONCLUSION

Municipal solid waste (MSW) composition recovery-oriented assessment demonstrates that substantial embedded value is found in the material and energy pathways. The 77 regional composition profiles (19992022) analyzed show that, in most cases, over four-fifths of the waste stream can be theoretically recovered via recycling and composting, while the combustible portion still has a moderate calorific potential that can be used in thermochemical recovery. The main types of levers to improve the diversion and recycling of resources are paper, food waste, and plastics, making them the most dominant elements. The potential energy according to the profiles with sufficient detail on combustibles demonstrates that residual streams can be used in waste-to-energy applications, in the case of the correct application of technical and environmental regulations. The regional variation was greater than the temporal variation, indicating that the composition aspect causes more variation than long-term structural changes. The composite Waste-to-Value Index also emphasizes the fact that maximum performance is achieved when calorific suitability and material recovery are balanced as opposed to depending on one particular avenue. Combined, these results are conducive to integrated recovery strategies involving source separation, organics management and controlled energy recovery. The indicators based on composition suggest a convenient basis to prioritize investments and implement a locally designed waste-to-value system based on the goals of the circular economy.

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