



Original Research Article

The impact of recycling rates on energy recovery from Municipal Solid Waste: A comparative analysis of cities in Brazil and Mexico

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ABSTRACT

Brazil and Mexico are the largest economies and waste generators in Latin America, facing low recycling rates and heavy landfill reliance. A transition to sustainable management requires progressive recovery of both organic and dry waste. This study hypothesizes that concurrent organic diversion offsets lower heating value losses caused by dry recyclables recovery. Seven progressive recycling and organic diversion scenarios were modelled across three contrasting urban scales: Santo André, Mexico City, and Guadalajara. Results show that organic diversion reduces weighted waste moisture down to 47.2%, stabilizing energy potential and achieving up to 81.5% landfill diversion. Based on a 2.437 MWh_{year}⁻¹ baseline, the recovered electricity

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could power over 750,000 households in Mexico City, supporting urban energy transitions aligned with Brazil's Solid Waste Plan goals.

KEYWORDS

Municipal solid waste, waste-to-energy, recycling, gravimetric composition, sustainability, landfills, material flow analysis.

INTRODUCTION

Brazil and Mexico stand out as the most populous countries and the largest economies in Latin America and the Caribbean (LAC), both ranking among the top 20 global economies [1]. Consequently, they are the primary generators of Municipal Solid Waste (MSW) in the region, accounting for more than 50% of the 230 million tonnes generated annually [2]. In these emerging economies, rapid economic and technological growth has escalated waste generation. Although regulatory frameworks increasingly promote circular economy goals, local adoption remains hindered by institutional gaps [3].

In the Brazilian context, the population surpassed 212 million inhabitants in 2024 [4]. In 2023, the country generated approximately 81 million tonnes of MSW, of which nearly 71 million tonnes were collected. However, about 48% of total waste generated—approximately 40 million tonnes—was disposed of in controlled landfills or open dumps lacking adequate environmental protection [5]. Furthermore, the effective recycling rate for dry materials remains alarmingly low, at approximately 2.69% of the total generated mass [6].

This management landscape is governed by the National Solid Waste Policy (PNRS), established by Law No. 12,305/2010. Inspired by international standards, the PNRS mandates a waste management hierarchy prioritizing non-generation, reduction, reuse, recycling, and treatment over final disposal [7]. More recently, the National Solid Waste Plan (Planares), updated by Decree No. 11,043/2022, reinforced these objectives by setting ambitious targets to close dumpsites and explicitly identifying selective collection and energy recovery as key strategies to divert waste from landfills [8].

Conversely, Mexico, with a population of approximately 130 million [9], generates about 40 million tonnes of MSW annually. According to the Secretariat of Environment and Natural Resources, while 85–90% of waste is collected, only about 65% reaches controlled disposal sites, leaving a significant 30% improperly discarded [10]. Despite being a global leader in specific fractions such as PET recycling, Mexico's overall recycling and composting rates remain below 7% [11], mirroring the systemic waste recovery challenges faced by Brazil.

Although Brazil generates nearly double the total waste of Mexico with a population only 60% larger—indicating a more intensive per capita disposal pattern—the two nations share striking similarities. Both possess highly urbanized populations and face a critical need to reduce landfill volumes. The transition toward a circular economy in both nations is constrained by a heavy reliance on landfills and the slow integration of advanced treatment technologies, making a comparative study of their management systems both methodologically robust and timely.

Simultaneously, both nations face the urgent challenge of energy transition and decarbonization. Brazil and Mexico must diversify their energy matrices while meeting the growing electricity demand of their expanding urban centres. In this context, Waste-to-Energy (WtE) technologies emerge as a synergistic solution. By converting the non-recyclable fraction of MSW - including textiles, sanitary products, and contaminated or non-recyclable polymers into electricity or heat, these countries can concurrently address environmental management deficiencies and contribute to a cleaner energy supply.

Energy recovery represents a fundamental link between sanitation and energy policies. For countries characterised by a high concentration of organic fractions and low recycling rates in their MSW, WtE offers a viable pathway to drastically reduce landfill volumes while mitigating emissions of methane—a potent greenhouse gas. As observed in other rapidly growing urban

centres across emerging economies, such as Jakarta, implementing WtE technologies is increasingly regarded as a critical route toward achieving sustainable urban environments [12]. Nevertheless, technical and economic barriers continue to delay the large-scale implementation of thermochemical WtE processes in Latin America and the Caribbean [13].

A persistent concern among decisionmakers regarding investment in WtE infrastructure is whether ambitious recycling targets might compromise facility viability by removing high-calorific materials. Conversely, while high recycling targets are essential for circular economy strategies, thermal energy recovery facilities remain an indispensable, complementary component of integrated waste management, acting as a final sink to safely destroy hazardous organic contaminants and process non-recyclable residual fractions [14].

Consequently, studies investigating the combined effect of diverting recyclable materials and organic fractions on the heating value of waste delivered to WtE plants are fundamental. Previous research has addressed this relationship through distinct lenses: on the one hand, laboratory models have established that moisture content in the organic fraction reduces MSW Lower Heating Value (LHV) more sharply than the removal of dry recyclables, with food waste identified as the primary negative driver of LHV [15]. Furthermore, longitudinal evaluations demonstrate that intensive source separation of organic waste significantly elevates the LHV of the residual stream, effectively transforming it into a Refuse-Derived Fuel (RDF) feedstock; however, overall reductions in mass flow can alter plant economies of scale and favour co-combustion routes over dedicated mass-burn incineration [16]. On the other hand, evidence from operational WtE systems suggests that higher recycling rates do not necessarily compromise WtE viability: in the European Union, increasing recyclables separation to 48% reduced the residual fraction available for WtE to approximately 25%, introducing feedstock heterogeneity without preventing the coexistence of both systems [17]; similarly, US communities operating WtE facilities reported recycling rates approximately one percentage point above the national average [18].

Regional assessments confirm that organic matter dominates waste streams in Latin America, accounting for 50% to 60% of total MSW; however, its valorization remains severely constrained by underdeveloped infrastructure [2]. Moreover, the broader transition to circular waste management in the region continues to be hindered by systemic institutional, financial, and regulatory barriers [3]. Thus, Latin American cities combine persistently low recycling and composting rates with an underdeveloped organic valorisation infrastructure, highlighting the urgent need for region-specific studies.

Comprehensive reviews focusing on waste in Mexico and Latin America and the Caribbean reiterate that high organic fractions and elevated moisture contents are primary limiting factors affecting mechanized sorting systems [19], energy recovery potential, and RDF performance [2]. Within the Brazilian literature, extensive research addresses solid waste energy recovery across multiple domains, including environmental lifecycle assessments of combined energy recovery technologies [20]; techno-economic analyses of MSW gasification across different municipal scales [21]; electricity generation potential evaluations in Santo André [22] and across São Paulo State municipalities [23]; and the characterisation of RDF produced from rejects in São Paulo [24] and Minas Gerais [25].

Previous Material Flow Analysis (MFA) and WtE studies have established that dry-recyclables recovery and organic-waste diversion significantly alter waste streams, though often analysed in isolation. European assessments using parameterized MFA demonstrate that intensified source separation of plastics and paper lowers the overall gross energy potential of residual waste [26]. However, to the best of the authors' knowledge, no study has jointly modelled the interaction between progressive dry-recyclables recovery and organic-waste diversion concerning WtE performance indicators in Latin American megacities using primary experimental data. Thus, this study hypothesizes that concurrent organic-waste diversion can offset lower heating value losses associated with increased dry-recyclables recovery, stabilizing—rather than compromising—the energy recovery potential of MSW.

This study addresses this gap by jointly modelling seven scenarios of recycling and organic diversion across three municipalities with contrasting scales and data availability: Santo André, whose primary moisture and ash content data ground the LHV estimates used across all three cities; Guadalajara, a mid-sized metropolitan region with limited primary characterisation data; and Mexico City, a megacity representative of the extreme urban densities found in the region.

The selection of these cities is justified by a fundamental dynamic in South Global MSW management: the coexistence of densely populated megacities with greater infrastructure access versus intermediate regional hubs facing operational constraints[27]. The analysis of Mexico City, Guadalajara, and Santo André establishes a gradient representative of Latin American urban scales, enabling a comparative assessment of energy recovery strategies across heterogeneous operational contexts.

The innovative contribution of this work is twofold: it provides, to the best of the authors' knowledge, the first joint quantification—using primary experimental data—of how dry-recyclables recovery and organic diversion interact to affect WtE performance in Latin American cities, while offering a transferable methodological approach for other cities facing similar data limitations. Accordingly, this study aims to evaluate the MSW energy recovery potential in Santo André (Brazil), Guadalajara, and Mexico City (Mexico) by examining the thermochemical sensitivity of waste across seven progressive scenarios aligned with both Planares 2040 targets and international circular economy benchmarks.

MATERIAL AND METHODS

This section describes the methodological approach adopted to characterise waste generation, model the proposed management scenarios, and estimate their impact on energy recovery and landfill diversion across the three studied municipalities.

Demographic and waste generation indicators

The initial phase of this research involved surveying secondary data to quantify Municipal Solid Waste generation and set a baseline for energy recovery modelling. To ensure technical reliability, data were retrieved from official national and regional inventories across Brazil and Mexico, including demographic projections, per capita generation rates, gravimetric compositions, and local energy consumption patterns. This multi-source approach allowed for the harmonisation of diverse datasets, providing the necessary inputs for the Material Flow Analysis (MFA). The parameters utilized, alongside their respective institutional sources, are summarized in Table 1.

Table 1. Secondary data and sources for evaluating the MSW generation and composition of each municipality.

Data Category	Reference Source		
	Santo André (SA)	Mexico City (CDMX)	Guadalajara (G)
Population	[4]	[9]	[9]
MSW generation rate	[6]	[10]	[11]
Gravimetric Composition	[28]	[10]	[11]
Moisture and Ash Content		[22]	

Material flow analysis and waste fraction characterisation

To systematically track the mass and energy distribution along the waste pathway, a Material Flow Analysis (MFA) was implemented. This framework models the transition of waste from the point of generation through three distinct collection pathways: undifferentiated collection, source-segregated dry recyclables, and source-segregated organic waste (Figure 1).

To assess the impact of these streams on the energy recovery potential, the MSW was further categorised into four functional fractions based on their physical-chemical properties and recovery suitability:

- **Combustible Fractions:** Comprising high-calorific components such as non-recyclable paper and plastics, textiles, sanitary products, and organic matter. These materials represent the primary feedstock for thermal recovery due to their significant LHV.
- **Dry Recyclables:** Focused on materials destined for the circular economy, including paper, cardboard, plastics, glass, and metals. The recovery of these materials directly influences the energy density of the remaining waste stream.
- **Organic Fractions:** Consisting primarily of food and green waste. While these fractions can be recovered for energy (e.g., via anaerobic digestion), their high moisture content typically poses a challenge for direct combustion processes.
- **Inert Waste:** Composed of non-combustible and non-recyclable materials that do not contribute to energy recovery, generally destined for final disposal.

The classification of waste fractions and the respective technological pathways adopted in this modelling are systematized in Figure 1. The first flowchart (Figure 1a) details the segregation of municipal solid waste (MSW) into the functional groups previously defined, allowing for a precise analysis of the gravimetric composition available for each stream. The second flowchart (Figure 1b) illustrates the Material Flow Analysis (MFA) from generation to final destination, integrating collection and treatment systems. The primary focus of this research was to investigate how progressive increases in dry waste recycling rates and source-segregated organic waste collection influence the physical-chemical properties of the residual mass, directly impacting the electrical energy recovery potential via the mass burning process.

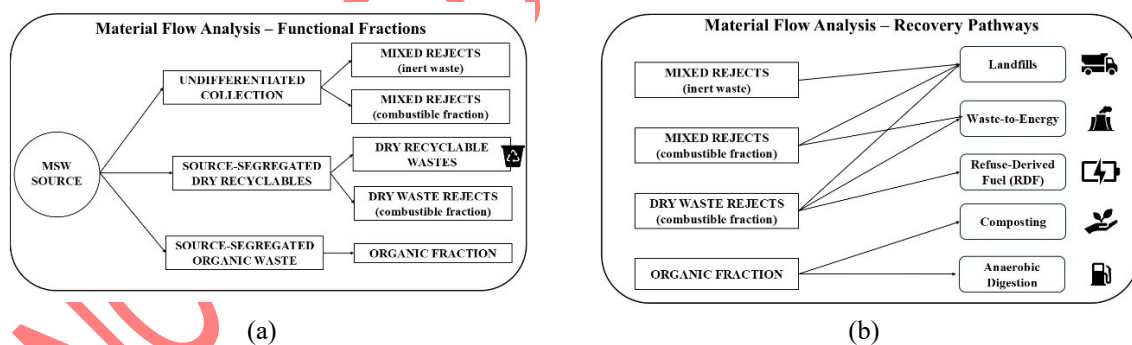


Figure 1. Classification of MSW functional fractions and material flow analysis for recovery pathways: (a) functional fractions; (b) recovery pathways.

Scenarios definition

Mathematical modelling and scenario-based simulations serve as essential tools for decision-makers to evaluate the best trade-offs between waste availability and energy recovery efficiency [29]. The use of normative scenarios to guide urban sustainability has been previously explored for Brazilian contexts, such as Rio de Janeiro, emphasizing the need for integrated resource management [30]. In this work, to evaluate the technical and energetic sensitivity of the system, seven progressive scenarios were modelled, simulating the transition from current practices to high-performance management targets.

To define the scenarios, enhancements to the Recovery Rate of Dry Recyclables (RDR) were determined by considering both the expansion of selective collection systems and the efficient processing of recyclable materials. Concurrently, the Recovery Rate of Organic Waste

(RDO) was integrated as a fundamental driver for urban sustainability and circularity and thermodynamic enhancement of the remaining waste fractions. Reducing the organic mass — and its associated high moisture content — directly improves the **LHV** of the combustible stream, thereby optimizing mass-burn energy recover.

- **Scenario 1 (SC1) – Baseline:** Represents the current municipal solid waste management situation in the three municipalities, characterised by predominant undifferentiated collection and baseline recycling levels (RDR and RDO at current empirical rates).
- **Scenarios 2.1 to 2.3 (SC2 series) – Planares 2040 Targets:** These scenarios adopt a fixed RDR of 25%, aligned with the 2040 targets established by the Brazilian National Plan for Solid Waste (Planares) for Brazilian Southeastern region [6]. This rate is evaluated against three progressive organic diversion levels (RDO): 0% (SC2.1, representing no organic diversion), 20% (SC2.2, representing an intermediate decentralised composting/anaerobic digestion target), and 45% (SC2.3, reflecting the full Planares 2040 target for organic waste recovery)
- **Scenarios 3.1 to 3.3 (SC3 series) – Advanced Circular Economy:** Proposes an ambitious 40% RDR index for dry recyclables, reflecting performance benchmarks in developed circular economy frameworks [13]. Similar to SC2 series, this high recycling rate is tested against the same three organic diversion levels: 0% (SC3.1), 20% (SC3.2), and 45% (SC3.3) to evaluate the combined integration with organic waste management.

For all scenarios, the residual waste stream remaining after material recovery was directed to a mass-burn incineration process for electricity generation, enabling the systematic assessment of how progressive source segregation impacts thermal efficiency, fuel quality, and net energy output. The scenario parametrization is summarized in Table 2.

Table 2. Definition of waste management scenarios based on dry recyclable and organic diversion rates

Scenario	Recovery Rate of Dry Recyclables (RDR)	Recovery Rate of Organic Waste (RDO)	Reference / Policy Benchmark
SC1	Current Scenario	Current Scenario	Empirical baseline data
SC2	2.1	0%	Planares 2040 target for dry recyclables [8]
	2.2	20%	Planares 2040 dry target [8]+ Intermediate organic diversion
	2.3	45%	Full Planares 2040 targets for dry and organic fractions [8]
SC3	3.1	0%	Advanced circular economy benchmark for dry recyclables (organic control) [31]
	3.2	20%	Advanced circular economy benchmark (intermediate organic diversion)
	3.3	45%	Advanced circular economy benchmark (full organic diversion)

Mathematical Modelling and Calculation Procedures

The modelling approach comprised four sequential stages: mass balance calculations across all seven scenarios, estimation of electrical energy recovery via mass-burn Waste-to-Energy (WtE), evaluation of landfill diversion rates, and the assessment of system performance indicators.

Mass Balance: For each of the proposed scenarios, a mass balance was carried out by applying the indices corresponding to the recovery of dry recyclables (RDR) and organic waste (RDO) (Table 2) to the baseline values Scenario (SC1). The mass of dry recyclable fractions recovered through source segregation was determined by applying the RDR index to the initial mass of each corresponding recyclable component in the undifferentiated collection, as expressed in Eq. (1):

$$MSW_{rf,i} = RDR \times MSW_{rf,i} \quad (1)$$

Simultaneously, the mass of recovered organic wastes was determined by applying the RDO index to the total initial mass of organic waste, according to Eq.(2):

$$MSW_{rof} = RDO \times MSW_{of} \quad (2)$$

Subsequently, the new gravimetric composition of the residual (unrecovered) waste stream was estimated. The new mass for each waste component was calculated by difference, as shown in Eq. (3):

$$UnMSW_j = MSW_j - MSW_{rf,j} - MSW_{rof} \quad (3)$$

Where $MSW_{rf,i}$ is the recovered mass of dry recyclable fraction i [t]; $MSW_{rf,i}$ is the initial total mass of dry recyclable fraction i [t]; RDR is the recovery rate of dry recyclable materials [%]; MSW_{rof} is the total recovered mass of organic waste [t]; MSW_{of} is the initial total mass of organic waste [t]; RDO is the recovery rate of organic waste [%]; $UnMSW_j$ is the remaining unrecovered mass of waste fraction j [t]; MSW_j is the initial total mass of waste fraction j [t]; $MSW_{rf,j}$ is the recovered mass of dry recyclable fraction j [t]; i represents the dry recyclable waste fractions (paper, cardboard, plastics, metals, textiles); and j represents all evaluated waste fractions (including organics and inerts).

Estimation of electrical energy recovery from waste-to-energy: In this study, it was assumed that all unrecovered combustible waste fractions following source segregation were directed to a mass-burn Waste-to-Energy (WtE) facility. This assumption represents the maximum technical potential under full WtE deployment rather than a short-term operational forecast. As none of the three municipalities currently operate WtE infrastructure, achieving the diversion and energy recovery rates presented here would require substantial capital investment—typically in the range of tens to hundreds of millions of USD for facilities of this scale [20]—phased implementation, and dedicated policy support, with project amortisation and economic payback periods commonly spanning 7 to 15 years. Consequently, these scenarios serve as upper-bound benchmarks for strategic policy planning.

To estimate the electricity output, a mass-burning incineration system was considered. The annual electrical energy generated (E_g) was calculated according to Eq. (4)[23]:

$$E_g = 0.28 \times MSW_{\text{fuel}} \times LHV_{\text{total}} \times E_e \quad (4)$$

Where E_g is the theoretical electrical energy generated [MWh year^{-1}]; MSW_{fuel} is the total annual mass of MSW fuel fractions destined for the WtE facility [t year^{-1}]; LHV_{total} is the lower heating value of the residual MSW stream [GJ t^{-1}]; 0.28 is the unit conversion constant [MWh GJ^{-1}]; E_e is the thermal-to-electrical transformation efficiency.

The thermal-to-electrical transformation efficiency (E_e) of modern mass-burn facilities typically ranges between 20% and 35%, depending on plant scale, steam parameters, and heat recovery configuration. In this work, to evaluate the range of potential energy generation, lower and upper bound net electrical efficiencies of 25% and 35% were adopted, respectively. These values account for internal parasitic electricity consumption by auxiliary equipment — such as forced-draft fans, flue gas cleaning systems, and feed pumps — establishing a robust sensitivity range for comparative scenario analysis across the evaluated municipalities [32].

To account for unscheduled downtime, periodic boiler cleaning, and routine maintenance, an operational availability factor based on 8,000 annual operating hours was adopted, yielding an availability reduction factor of 0.91 [33]. This value represents an established international industrial benchmark for commercial mass-burn WtE plants, reflecting a realistic annual capacity factor of approximately 91.3%. The total electrical energy effectively generated in a year ($E_{g,\text{total}}$) was estimated using Eq.(5):

$$E_{g,\text{total}} = 0.91 \times E_g \quad [\text{MWh year}^{-1}] \quad (5)$$

The total mass of combustible waste (MSW_{fuel}) was derived from the mass balance calculations by summing all remaining combustible components, according to Eq. (6):

$$MSW_{\text{fuel}} = \sum_k UnMSW_{f,k} \quad (6)$$

Where $UnMSW_{f,k}$ is the unrecovered mass of combustible MSW fraction k ; and k represents the combustible waste components (paper/cardboard, textiles, plastics, organics and sanitary items)

The lower heating value of the residual waste mixture was estimated using an empirical mathematical model which was previously validated with statistically representative samples to correlate gravimetric fractions and moisture content [28], as expressed in Eq. (7):

$$LHV_{\text{wb}} = [(15.42Or + 19.14Sa + 32.68Pl + 8.33Pa + 21.51T) \times (1 - W)] - (2.442 \times W) \quad (7)$$

Where LHV_{wb} is the wet-basis lower heating value [MJ kg^{-1}]; W is the total moisture content [gravimetric fraction]; Or is the organic mass fraction; Sa is the sanitary waste mass fraction; Pl is the plastic mass fraction; Pa is the paper mass fraction; and T is the textile mass fraction.

A central methodological feature is the dynamic recalculation of the weighted average moisture for each scenario. This allowed for the direct evaluation of how progressive organic and recyclable recovery alters the LHV of the fuel stream. Due to the limited availability of primary physical characterisation data in the Mexican municipalities, experimental moisture and ash parameters determined for Brazilian MSW were adopted as a uniform baseline,

justified by their statistical reliability and laboratory rigor under Latin American urban conditions.

Landfill Diversion Rate estimation: The mitigation of disposal pressure on sanitary landfills was quantified through the Landfill Diversion Rate (LDR), comparing the baseline disposal of Scenario 1 (SC1) with the residual masses generated in the proposed scenarios. This indicator assesses the effectiveness of policy targets (e.g., Planares)[8] and international best practices in extending the operational lifespan of final disposal infrastructure and reducing associated environmental liabilities.

The total mass directed to sanitary landfills (MSW_{landfill}) was determined by aggregating three primary material streams: (i) residual ash generated from the combustion of combustible fractions; (ii) operational *bypass* mass, representing waste diverted during thermal plant maintenance or downtime (based on the plant availability factor of 0.91); and (iii) non-recyclable inert fractions alongside sorting rejects. The cumulative mass for final disposal was calculated according to Eq. (8):

$$MSW_{\text{landfill}} = \sum_k [UnMSW_{f,k} \times (1 - W_k) \times AC_{f,k}] + (0.09 \times MSW_{\text{fuel}}) + \sum_g MSW_{\text{rrf},g} \quad (8)$$

Where MSW_{landfill} is the total mass of waste directed to sanitary landfills [t year^{-1}]; $AC_{f,k}$ is the ash content in combustible fraction k [dry basis, %]; W_k is the moisture content in combustible fraction k [gravimetric fraction]; MSW_{fuel} is the total annual mass of MSW fuel fractions destined for the WtE facility [t year^{-1}]; $MSW_{\text{rrf},g}$ is the mass of unrecovered inert waste from non-combustible fraction g [t year^{-1}]; k represents the combustible fractions (organics, sanitary, plastics, paper, textiles); and g represents the non-combustible inert fractions (glass, metals, ceramics, and others).

It is important to emphasise that, due to the limited availability primary physical characterisation data for the Mexican municipalities, the estimation of ash content was based on experimental laboratory measurements previously conducted by the authors' research group. These trials utilized standardized protocols and statistically representative samples from Santo André [22], ensuring methodological consistency and technical reliability for this comparative assessment.

Performance indicators: To evaluate the efficiency of the proposed scenarios and their alignment with circular economy principles, a set of performance indicators was calculated based on metrics adapted from the Brazilian National Solid Waste Plan (Planares) [8]. These indicators allow for a quantitative comparison of how each management configuration contributes to material recovery and the reduction of final disposal needs:

- Mass Recovery Rate of Dry Recyclables (TR_{rs}): Measures the percentage of paper, plastic, glass, and metals diverted from the total waste stream toward recycling chains.
- Mass Recovery Rate of Organic Waste (TR_{ro}): Quantifies the effectiveness of source-segregated organic collection and its diversion to biological treatment (composting or anaerobic digestion).
- Integrated Recovery Rate (TR_{rso}): Represents the combined effort of both dry and organic material recovery, serving as a key proxy for system circularity.
- Landfill Diversion Rate (TD_{land}): The overall indicator accounting for the total waste mass diverted from sanitary landfills through the combined effect of material recycling and mass-burn Waste-to-Energy (WtE).

- Net Energy Generation ($E_{g, \text{total}}$): Represents the net annual electrical energy produced through WtE [MWh year^{-1}], reflecting the available output after accounting for plant availability, parasitic load, and dynamic lower heating value (LHV) across scenarios
- Equivalent Serviced Residences (N_{res}): A social-reach indicator estimating the number of households whose electricity demands could be supplied by the recovered energy. The calculation adopts an average residential consumption baseline of $2.437 \text{ MWh year}^{-1}$ per household [8], ensuring regional representativeness and alignment with public policy standards.

The definition and computational basis for these performance indicators are summarized in Table 3Table 1. They were calculated for all three municipalities across the seven evaluated scenarios.

Table 3. Performance Indicators calculated for each Scenario

Performance Indicator	Description/Formula	Unit
Mass Recovery Rate of Dry Recyclables (TR_{rs})	Total mass of dry waste recovered/ Total MSW generated	%
Mass Recovery Rate of Organic Waste (TR_{ro})	Total mass of organic waste recovered/ Total MSW generated	%
Integrated Recovery Rate (TR_{rso})	Total mass of recovered material (dry + organic)/Total MSW generated	%
Landfill Diversion Rate (TD_{land})	$[1 - (\text{MSW}_{\text{landfill}}/\text{MSW}_{\text{total}})] \times 100$	%
Net Energy Generated	Net annual electrical energy generated via WtE (Eq. 5)	MWh year^{-1}
Equivalent serviced residences (N_{res})	Estimated household coverage baseline [21] ($E_{g, \text{total}}/2.437$)	Households

Uncertainty and methodological considerations

To evaluate the comparative performance of the proposed scenarios, deterministic mass and energy balances were conducted. Certain methodological assumptions were adopted due to data availability constraints and the baseline evaluation scope:

- Transferability of physical-chemical parameters: primary laboratory characterisation for moisture (W_k) and ash content ($AC_{f,k}$) determined for Brazilian municipal solid waste (Santo André) [22] was applied across all three evaluated municipalities. This baseline selection is supported by the physical similarities in waste composition and organic fraction dominance documented for Mexican municipal waste streams [2]. Adopting these validated experimental values provides a consistent, high-reliability physical baseline in the absence of complete local elemental and thermochemical datasets for the studied Mexican municipalities.

- Operational parameters: Key thermochemical parameters—specifically the plant operational availability of 8,000 hours year⁻¹ (Eq. 5) [33] and the net conversion efficiency range of 25% to 35% (Eq. 4) [32]—were maintained across all modelled configurations. The lower and upper bounds of net electrical conversion efficiency (25% for baseline commercial mass-burn plants and 35% for higher-efficiency facilities) represent standardized benchmarks reported in the literature, accounting for planned maintenance outages, parasitic auxiliary electricity consumption, and technological variations.

While dynamic operational fluctuations (such as seasonal moisture shifts or localized plant downtime) may induce variations in real-world energy yields, maintaining these baseline assumptions ensures a harmonized, reproducible framework. Consequently, the modelled scenarios should be interpreted as technical energy recovery potential indicators for policy evaluation rather than stochastic operational forecasts.

RESULTS AND DISCUSSION

This section presents the waste generation and compositional characterisation of the three municipalities, followed by the modelling results for energy recovery, landfill diversion, and overall system performance under each scenario.

Municipalities characterisation: wastes generation and properties

The annual municipal solid waste (MSW) generation for each studied city was estimated by integrating the most recent official population projections with specific per-capita generation rates. As shown in Table 4, these rates were derived from a combination of primary data and updated local technical reports to ensure the representation of both residential and non-residential urban streams. Additionally, Table 4 presents current demographics and baseline dry waste recycling indices for each municipality, providing the necessary context for the subsequent energy recovery scenarios.

Table 4. Demographic and waste generation data for Santo André, Mexico City and Guadalajara

Secondary Data	Santo André	Mexico City	Guadalajara
Population (inhab)	782,048 ^(a) [4]	9,209,944 [9]	1.6 million [9]
MSW generation rate (kg.inhab ⁻¹ .day ⁻¹)	0.8 [6]	1.4 [11]	0.998 [35]
MSW generation (t. year ⁻¹)	228,358.02	4,706,281.38	582,832.00
Actual recovery dry recyclable materials index ^(b) (wt, %)	1.05% [6]	1.8 – 2.5 [9]	3.5 – 5 [35]

Legend: **(a)** Estimated population for 2025; **(b)** Mass of dry recyclable waste recovered/ total MSW mass

According to the most recent census, the municipality of Santo André had a population of 748,919 in 2022. Based on official growth projections, the population is estimated to reach 782,048 inhabitants by 2025 [4]. Regarding waste metrics, data from the National Sanitation Information System (SNISA) for 2024 [6] indicates a per-capita household waste collection rate of 0.8 kg inhab⁻¹.day⁻¹, totalling approximately 228,358 t year⁻¹ of MSW generated. Furthermore, the municipality achieves door-to-door selective collection coverage, with a reported recovery index of 1.05% for dry recyclables —consistent with the recovery index reported in Table 4— which serves as the baseline for the recycling scenarios analysed in this study [6]. Regarding Mexican municipalities, data from Mexico City (CDMX) indicate a per-capita generation rate of

1.40 kg inhab⁻¹·day⁻¹, with a total annual generation exceeding 4.7 million tonnes [34]. This high value includes contributions from residential (48.1%), commercial (25.7%) and service (13.8%) waste streams under municipal jurisdiction, reflecting the high urban density and consumption patterns of the capital [10]. In contrast, data for Guadalajara reveals methodological nuances; while field sampling across Jalisco municipalities yielded a domiciliary waste generation rate of 0.607 kg inhab⁻¹·day⁻¹, survey-based integrated estimates averaged 0.998 kg inhab⁻¹·day⁻¹ [35]. The difference of approximately 0.391 kg inhab⁻¹·day⁻¹ is attributed to non-domiciliary sources, such as small commercial establishments. To ensure a fair comparison with Santo André and CDMX, this study adopted the broader rate (0.998 kg inhab⁻¹·day⁻¹) for Guadalajara, as it better represents the overall municipal waste stream.

The waste generation rates observed in the studied municipalities reflect a direct correlation with urbanisation and economic development, consistent with patterns identified across Latin America and the Caribbean. Per capita generation in Santo André (0.8 kg inhab⁻¹·day⁻¹) aligns closely with the regional average of 0.90 kg inhab⁻¹·day⁻¹ projected by the World Bank [34]. In comparison, the City of São Paulo—the largest Brazilian megacity—reports a similar integrated rate of 1.10 kg inhab⁻¹·day⁻¹, further validating the magnitude of the data adopted for the ABC region. Both Brazilian cases demonstrate a performance in dry waste recovery (1.05% in Santo André and 1.26% in São Paulo) that remains significantly below their gravimetric potential, highlighting a common challenge in integrated regional management.

In contrast, Mexico City (CDMX) exhibits a significantly higher generation rate (1.40 kg inhab⁻¹·day⁻¹), positioning it as one of the primary waste generators among global megacities, trailing only the New York region. This disparity can be attributed to its extreme urban density, accelerated consumption patterns, and its status as the third-most populated agglomeration worldwide. While North American high-income nations (Bermuda, Canada, and the United States) reach averages of 2.21 kg inhab⁻¹·day⁻¹, the values for CDMX and Guadalajara (0.98 kg/day) represent an intermediate stage of waste-income elasticity [34]. These variations in generation and recycling performance (Table 4) provide the essential framework for evaluating the feasibility of the energy recovery scenarios proposed in this study.

Current recycling rates in the studied municipalities—1.05% in Santo André and approximately 1.8–5.0% in the Mexican cities — reveal a significant gap compared to international benchmarks. While the Brazilian National Plan for Solid Waste (Planares) sets a target of 40% recycling for the Southeast region, current performance remains far below this goal [8]. In contrast, European standards emphasise a circular economy framework where recycling targets reach up to 65% by 2035 [26].

The high reliance on landfilling in Brazil and Mexico not only represents a critical loss of secondary raw materials but also limits the immediate availability of high-calorific fractions for energy recovery. These results demonstrate that both countries have a substantial pathway ahead to reach international benchmarks, both in terms of material recycling and waste-to-energy conversion. Given that commercial WtE infrastructure remains at a design or planning stage in these regions, facility sizing must explicitly account for prospective shifts in selective collection and the dual recovery of wet and dry waste streams.

The baseline gravimetric composition for each municipality is presented in

Table 5 and Figure 2. Consistent with municipal waste profiles typical of emerging economies, the organic fraction constitutes the predominant component across all sites. Santo André exhibited the lowest organic share at 38.79%, closely aligning with Mexico City at 42.57%, whereas Guadalajara recorded the highest proportion at 48.00%. Sanitary waste ranged from 10.80% to 14.46%, with the lowest share observed in Santo André and the highest in Mexico City.

Table 5. Gravimetric composition of current scenario for each studied municipality (% wet weight).

Fraction	Gravimetric composition (% wet weight)				
	Santo André		Mexico City		Guadalajara
	Range	Average	Range	Average	Average
Organic Matter	17.83 – 70.81	38.79	37.83 – 45.57	42.57	48.00
Sanitary	1.51 – 27.83	10.80	10.98 – 17.84	14.46	11.00
Plastic	5.59 – 22.08	14.77	15.03 – 17.21	15.86	11.50
Paper	1.35–23.00	11.12	11.0 – 20.04	13.69	12.00
Textiles	0.16–32.99	8.94	3.0 – 8.1	4.41	1.80
Other recyclable		5.74	1.89 – 4.36	3.27	6.50
Other	15.58	9.84	3.38 – 7.63	5.74	9.20
Source	[28]		[36]		[35]

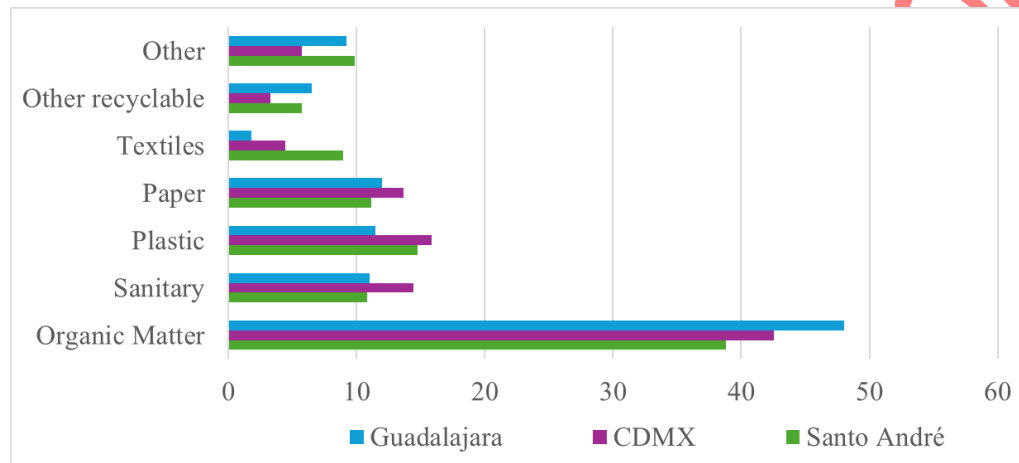


Figure 2. Average gravimetric composition considered for baseline scenarios in Santo André [28], Mexico City [10], and Guadalajara [35].

Dry recyclable materials (plastics, paper/cardboard and others recyclable, such as glass and aluminium, for example) accounted for approximately 30% of total MSW across all three municipalities. In this study, textiles were excluded from the recyclable dry stream, as textile recycling technologies remain commercially limited in the studied regions. For Santo André, textiles represented 8.94% of the total mass, a figure comparable to major individual recyclable fractions such as plastics (14.77%) or paper/cardboard (11.12%). In contrast, textile fractions in Mexican cities were lower, registering 4.41% in Mexico City and 1.80% in Guadalajara.

It is important to note that gravimetric data for Santo André and Mexico City were derived from dedicated, site-specific physical characterisation trials, whereas data for Guadalajara were extracted from broader municipal management reports. This methodological distinction is significant, as observed variations stem not only from local consumption habits and socioeconomic factors, but also from differences in sampling protocols and gravimetric categorization methods.

The observed gravimetric composition across Santo André, Mexico City, and Guadalajara aligns with broader compositional patterns reported for emerging economies, while displaying contrasts with waste profiles in developed nations. Municipal solid waste across the Latin American region is characterised by a high organic content averaging $56.50 \pm 17.87\%$, which is substantially higher than the European average of $42.43 \pm 10.20\%$ [19]. In the evaluated municipalities, the organic fraction ranges from 38.79% in Santo André to 48.00% in Guadalajara. This dominance of fast-degradable organic matter (FD)—a signature feature of waste streams in developing economies, as also classified for Chinese urban centres [37]—is primarily driven by dietary habits, daily consumption of fresh foodstuffs, and less systemic food packaging prior to retail. Conversely, the share of slowly degradable materials (SD,

encompassing paper/cardboard, wood, and textiles) in the studied Latin American cities (~21.8% to 28.9%) remains well below the baseline of high-income developed countries, where SD fractions typically exceed 30–40% of total wet weight. The elevated proportion of FD waste combined with low initial source separation induces the moisture diffusion [37]. During storage and unsegregated municipal collection, free moisture from the high-water organic matrix (~65% to 80% wet basis) diffuses into porous dry fractions (such as paper and textiles). In Santo André and Mexico City, this moisture transfer increases the apparent water content of the dry combustible fractions, directly altering the overall weighted moisture profile of the unsegregated waste mass.

Furthermore, total recyclable dry materials (plastics, paper/cardboard, metals, and glass) accounted for approximately 30% of total MSW in all three municipalities, matching the Latin American average of $31.86 \pm 12.25\%$. However, while European waste management systems exhibit higher dry material shares supported by automated sorting and Extended Producer Responsibility (EPR) frameworks, material recovery in both Brazil and Mexico remains heavily constrained by a reliance on informal waste picking and underdeveloped secondary markets. Additionally, the non-trivial presence of textiles—reaching nearly 9% in Santo André compared to 1.8–4.4% in the Mexican cities—further illustrates the heterogeneous nature of the dry fraction across Latin American urban scales, which directly governs the physical structure and baseline energy density of the raw municipal stream. The determination of the LHV requires precise baseline data on specific thermochemical waste properties, most notably moisture and ash content. Despite their technical significance, these parameters are rarely available in official governmental reports or regional MSW characterisation literature. To address this data constraint, reference values derived from experimental research conducted in the municipality of Santo André were adopted, as detailed in Table 6 [22].

It is important to underscore that these moisture and ash content profiles were experimentally determined by the research group during prior primary sampling and laboratory campaigns [28]. These high-reliability primary data served as the input to calculate the weighted average moisture and elemental behaviour for each evaluated scenario, establishing a consistent physical baseline for both the mass balance formulation and the estimation of net energy recovery potential.

Table 6. Moisture and ash content for different combustible fractions of municipal solid waste from Santo André, São Paulo, Brazil [22].

Combustible Fraction	Moisture Content (%wb)	Ash Content (%db)
Organic Matter	65.47 ± 9.26	22.48 ± 11.56
Sanitary	52.27 ± 12.36	6.85 ± 2.07
Plastic	24.60 ± 8.50	6.67 ± 4.33
Paper	30.51 ± 10.47	10.13 ± 2.88
Textiles	32.26 ± 12.62	6.09 ± 5.36

Estimation of electrical energy recovery from waste-to-energy

The gravimetric compositions of combustible fractions, following the diversion of recovered dry recyclables and organic waste streams, alongside the Lower Heating Value (LHV) and the weighted average moisture (M) estimated for each scenario, across the studied municipalities, are presented in Table 7.

Table 7. Gravimetric composition, weighted average moisture (M) and LHV estimated for the MSW for municipalities of Santo André (Brazil), Mexico City and Guadalajara (Mexico), for different recovery rates of dry recyclables (RDR)

Santo André. BR								
Properties		SC1	SC2.1	SC2.2	SC2.3	SC3.1	SC3.2	SC3.3
M (%)		48.52	50.29	48.62	45.92	51.51	49.87	47.20
LHV [MJkg ⁻¹]		6.91	6.48	6.79	7.28	6.19	6.48	6.95
Gravimetric Composition	Or (%)	38.79	42.12	36.80	28.60	44.41	38.99	30.5
	Sa (%)	10.80	11.73	12.81	14.50	12.36	13.57	15.5
	Pl (%)	14.77	12.03	13.14	14.80	10.15	11.13	12.7
	Pp (%)	11.12	9.06	9.89	11.20	7.64	8.38	9.5
	Tx (%)	8.94	9.71	10.60	12.00	10.23	11.23	12.8
Ciudad de Mexico. MX								
Properties		SC1	SC2.1	SC2.2	SC2.3	SC3.1	SC3.2	SC3.3
M (%)		49.39	51.34	49.74	47.14	52.68	51.14	48.60
LHV [MJkg ⁻¹]		7.20	6.71	7.06	7.63	6.38	6.71	7.26
Gravimetric Composition	Or (%)	42.57	46.38	40.89	32.20	49.00	49.00	49.00
	Sa (%)	14.46	15.75	17.36	19.90	16.65	16.65	16.65
	Pl (%)	15.86	12.96	14.28	16.40	10.95	10.95	10.95
	Pp (%)	13.69	11.19	12.33	14.10	9.46	9.46	9.46
	Tx (%)	4.41	4.80	5.30	6.10	5.08	5.08	5.08
Guadalajara. MX								
Properties		SC1	SC2.1	SC2.2	SC2.3	SC3.1	SC3.2	SC3.3
M (%)		52.50	54.36	52.81	50.13	55.61	54.17	51.62
LHV [MJkg ⁻¹]		5.68	5.32	5.53	5.90	5.07	5.27	5.60
Gravimetric Composition	Or (%)	48.00	51.89	46.32	37.2	54.55	48.98	39.80
	Sa (%)	11.00	11.89	13.27	15.5	12.50	14.03	16.60
	Pl (%)	11.50	9.32	10.40	12.2	7.84	8.80	10.40
	Pp (%)	12.00	9.73	10.86	12.7	8.18	9.18	10.80
	Tx (%)	1.80	1.95	2.17	2.5	2.05	2.30	2.70

Legend: M = moisture content; LHV = Lower Heating Value; Or = organic fraction; Sa = sanitary fraction; Pl = plastic fraction; Pp = Paper fraction; Tx = textiles fraction

The data in Table 7 reveal that the weighted average moisture (M) of the waste streams varied between 45.9% and 55.6%, with the lowest values observed for Santo André and the highest for Guadalajara. The higher moisture content in the Mexican municipalities is primarily attributed to a more significant presence of the organic fraction. As expected, the isolated separation of dry recyclables (Scenarios SC2.1 and SC3.1) led to a relative increase in average moisture across all cities. High moisture is detrimental to the combustion-based energy recovery process, as it imposes a thermal penalty on the thermochemical process by consuming a substantial portion of released energy for water evaporation during the initial stages of grate combustion. This elevated water content in fast-degradable organic waste not only depresses the effective Lower Heating Value (LHV) of the mixed stream, but also causes moisture diffusion into porous dry fractions, further hindering autothermal combustion stability [37].

The results illustrate a clear trade-off between material recovery and energy density. In scenarios where only dry recycling is prioritised alone (SC2.1 and SC3.1), a significant reduction in LHV occurs—dropping by up to 11% in Mexico City (from 7.20 MJ kg⁻¹ down to 6.38 MJ kg⁻¹)—due to the selective removal of high-calorific fractions such as plastics and paper. However, the implementation of source-segregated organic collection (SC2.3 and SC3.3) acts as a critical corrective factor. By diverting 45% of the wet organic mass, the systematic reduction in moisture content neutralises the loss of dry combustible materials, allowing the residual LHV to return to or even exceed baseline levels (reaching 6.95 MJ kg⁻¹ in Santo André and 7.26 – 7.63 MJ kg⁻¹ in CDMX).

These findings corroborate the hypothesis that high circularity targets (40% recycling) are energetically compatible with mass burning technologies [26]. In fact, for Santo André and

CDMX, the synergistic management of both dry and organic streams optimized the "quality" of the fuel, ensuring thermodynamic feasibility for self-sustained combustion ($LHV > 7.0 \text{ MJ kg}^{-1}$) despite the reduction in total mass. Another noteworthy observation is the behaviour of the sanitary fraction (Sa). As recyclable materials are diverted, the relative proportion of sanitary waste increases—reaching nearly 20% in CDMX (SC3.3). Given its non-recyclable nature and lower moisture compared to food waste, this fraction becomes a significant "baseline fuel" for the WtE process in advanced management scenarios.

To establish the thermochemical baseline for individual fractions, this study relies on the primary experimental dataset generated for Santo André (Brazil) [22]. In that benchmark characterisation, the baseline LHV_{wb} for the mixed wet waste stream was determined at $7.22 \pm 1.76 \text{ MJ kg}^{-1}$, with category-specific lower heating values of 3.35 MJ kg^{-1} for organic matter, 7.33 MJ kg^{-1} for sanitary waste, 10.52 MJ kg^{-1} for paper/cardboard, and 22.97 MJ kg^{-1} for plastics [22]. Complementing this primary baseline, the discarded recyclable solid waste (DRSW) from the same sorting facility was evaluated, demonstrating that removing organics and inerts elevates the LHV_{wb} of the remaining stream to 19.86 MJ kg^{-1} *in natura* and up to 33.25 MJ kg^{-1} for non-chlorinated plastics [24]. Within the broader Brazilian context, a baseline LHV of 7.10 MJ kg^{-1} was established for unseparated municipal waste [20]. Assessing regional management strategies in São Paulo State, a LHV of 7.67 MJ kg^{-1} was documented for sanitary fractions [23]. Furthermore, it was demonstrated that intensive source separation drives residual waste calorific values toward solid recovered fuel (SRF) thresholds ($\sim 14.0 \text{ MJ kg}^{-1}$) [16]. These regional empirical profiles are further supported by the mathematical modelling, confirming that dry combustible fractions govern the overall energy yield of municipal streams [15].

It should be emphasised that the moisture parameters for the Mexican municipalities were estimated based on experimental data from Santo André, which introduces inherent analytical uncertainties. For instance, samples from Mexico City were analysed and reported an average moisture content of 33.7% (ranging from 14.6% to 49.8%), a figure lower than the baseline estimates adopted in this study [35]. Acquiring highly accurate moisture and calorific metrics across municipal contexts is inherently constrained by the extreme physical heterogeneity of incoming waste streams and localized sampling difficulties, including compaction practices and seasonal variations [15]. The thermodynamic implications of these variations were clearly demonstrated by authors that identified water content in fast-degradable organic waste as the primary thermal sink during combustion [37]. Despite these dynamic climatic and operational discrepancies, utilizing consistent experimental parameters from a single research group ensures a standardized baseline, which is essential for projecting realistic boiler efficiency, autothermal stability, and comparative energy recovery potential across the evaluated urban centres under identical management assumptions.

The consolidated results for electrical energy generation (E_{gen}) and social reach (N_{res}) across the seven scenarios are presented in Table 8. These figures represent the final output of the synergistic management strategy.

Table 8. Electrical Energy Generated (E_{gen}) and equivalent number of serviced residences (N_{res})

Santo André, BR							
Properties	SC1	SC2.1	SC2.2	SC2.3	SC3.1	SC3.2	SC3.3
$E_{gen, \text{ min}}$ [GWh.year ⁻¹]	84.85	73.50	69.31	64.07	66.74	62.53	57.27
$E_{gen, \text{ max}}$ [GWh.year ⁻¹]	118.79	102.91	97.03	89.69	93.43	87.54	80.17
$N_{res, \text{ min}}$	34,818	30,162	28,440	26,289	27,385	25,658	23,499
$N_{res, \text{ max}}$	48,745	42,226	39,816	36,804	38,339	35,922	32,899
Ciudad de Mexico, MX							
Properties	SC1	SC2.1	SC2.2	SC2.3	SC3.1	SC3.2	SC3.3

Egen, min [GWh.year ⁻¹]	1963.09	1681.82	1589.33	1474.58	1514.32	1421.12	1305.30
Egen, max [GWh.year ⁻¹]	2748.32	2354.55	2225.06	2064.41	2120.04	1989.57	1827.42
Nres, min	805,534	690,120	652,167	605,078	621,385	583,143	535,617
Nres, max	1,127,747	966,168	913,034	847,109	869,939	816,401	749,863
Guadalajara, MX							
Properties	SC1	SC2.1	SC2.2	SC2.3	SC3.1	SC3.2	SC3.3
Egen, min [GWh.year ⁻¹]	177.71	154.76	141.34	124.51	141.04	127.64	110.84
Egen, max [GWh.year ⁻¹]	248.79	216.67	197.88	174.31	197.46	178.70	155.18
Nres, min	729,22	63,505	57,997	51,090	57,876	52,377	45,483
Nres, max	102,090	88,907	81,196	71,526	81,026	73,328	63,677

Legend: Values for a corresponding thermal-to-electrical transformation efficiency $E_e = 25\%$ (min) and $E_e = 35\%$ (max)

The results presented in Table 8 show that Scenario 1, where all residual waste is directed to energy recovery, yields the highest electrical output and maximum household coverage. The range between the minimum and maximum values for electricity generation (E_{gen}) and household coverage (N_{res}) accounts for operational efficiency variations, where lower bounds correspond to a conservative net electrical conversion efficiency of 25% and upper bounds represent a high-efficiency benchmark of 35%. In all cities, transitioning from Scenario 1 (Baseline) to Scenario 3.3 (Advanced) leads to a reduction in total energy generation. In Mexico City, the maximum potential ($E_{gen,max}$) shifts from 2,748.32 GWh year⁻¹ to 1,827.42 GWh year⁻¹. Similarly, in Santo André, it drops from 118.79 to 80.17 GWh year⁻¹, and in Guadalajara, from 248.79 to 155.18 GWh year⁻¹. As expected, increasing the recovery of recyclable dry and organic waste reduces energy recovery by up to 38%.

This reduction is a direct consequence of diverting 40% of dry recyclables and 45% of organic waste, both of which represent significant combustible fractions. Although the LHV increases in Scenario 3.3 (as shown in Table 7), the gain in energy density per kilogram is insufficient to fully offset the 40-50% reduction in the total mass available for combustion. However, from a thermodynamic standpoint, the plant operates more efficiently in SC3.3, as the feedstock stream is drier, more stable and homogeneous.

To address why urban centres, exhibit disparate responses under identical management scenarios, it is necessary to examine the physical-chemical trade-offs driven by their baseline gravimetric distributions. A key finding lies in the performance of Guadalajara, which demonstrates both the highest relative loss in electrical generation (-37.63% in SC3.3 compared to -32.51% in Santo André and -33.51% in Mexico City) and a unique reduction in fuel quality. While Mexico City and Santo André achieve net LHV increases (+0.81% and +0.65%, respectively) in SC3.3, Guadalajara experiences a net LHV drop of -1.35%. This divergence illustrates the relative contributions of dry recyclable removal versus organic waste diversion. In Santo André and Mexico City, diverting 45% of organic matter removes a sufficient moisture load to shift the feedstock into a dry-dominated regime, overriding the calorific loss from diverting 40% of dry recyclables. Conversely, because Guadalajara starts with a heavier baseline organic fraction (48%), the 55% of residual organic waste left in the stream still imposes a substantial moisture burden. Removing 40% of high-calorific dry materials (plastics and paper) depresses the net LHV and magnify the overall energy reduction.

In evaluating these findings, a critical methodological limitation must be highlighted: unlike Santo André and Mexico City, where gravimetric characterisations were derived from standardized primary experimental campaigns, Guadalajara's baseline profile relied on secondary data sources. Such procedural discrepancies—ranging from local sorting protocols and seasonal sampling conditions—may introduce systematic uncertainties or artificially inflate the reported

organic share. This distinction not only provides a plausible explanation for the higher baseline organic fraction observed in Guadalajara but also underscores the necessity of implementing unified, standardized experimental characterisation frameworks when designing cross-border WtE management strategies.

A comparative analysis of the literature highlights that specific energy recovery potential (kWh t^{-1}) is strongly conditioned by waste composition and the defined boundaries of the technological system (Table 9). In developing contexts characterised by high moisture contents and significant organic fractions, such as the Brazilian scenarios, the Lower Heating Value (LHV) estimation of raw waste ranges between 6.45 [23] and 7.98 MJ kg^{-1} [20]. Under these conditions, direct mass-burn combustion routes achieve moderate electrical outputs ($\sim 400 - 530 \text{ kWh t}^{-1}$), whereas hybrid configurations integrating Anaerobic Digestion of the organic fraction with incineration of the dry fraction enhance net recovery up to 550 kWh t^{-1} [23]. The system sensitivity to the source-separation of dry recyclables (plastics and paper) is demonstrated by [38], where prior sorting drastically reduces the energy recovery potential of raw waste from $2,700 \text{ kWh t}^{-1}$ to 450 kWh t^{-1} . Conversely, when Waste-to-Energy (WtE) facilities process concentrated rejects from Materials Recovery Facilities (MRFs), as shown by [26], the LHV of the feedstock increases ($12 - 16.9 \text{ MJ kg}^{-1}$), yielding specific outputs of 588 kWh t^{-1} in high-efficiency WtE plants and 437 kWh t^{-1} in Integrated Gasification Combined Cycle (IGCC) systems. Furthermore, as highlighted by [21] for gasification with pre-treatment and drying (SRF), population scale and thermodynamic conversion efficiency exert a decisive influence on final energy viability, leading to substantial variations from 391 to $1,232 \text{ kWh t}^{-1}$ on a dry basis.

Table 9. Comparison of electrical energy recovery potential and municipal solid waste (MSW) characterisation across different technological and geographical contexts.

Source	Location	Technological Route / Scale	Organic Fraction (%)	Plastic + Paper (%)	LHV (MJ kg^{-1})	Specific Yield (kWh t^{-1})
[21]	Brazil	Downdraft Gasification + ICE (Variable scale)	52.6	28.5	19.63^a	$391-1,232^a$
[20]	Brazil	Mass-Burn Incineration (18% efficiency)	54.0	26.0	7.98^b	400^b
		Sanitary Landfill + ICE (46% recovery)				(Mass-Burn) 162^b (Landfill + ICE)
[23]	Brazil	Incineration + Anaerobic Digestion (Hybrid route)	44.3	23.7	6.45^b	550^b (Hybrid)
		Standalone Mass-Burn Incineration				530^b (Mass-Burn)
[38]	Ethiopia	Mass-Burn Incineration without sorting	68.0	15.4	9.72^b	$2,700^b$ (Unsorted)
		Incineration after recyclables sorting				450^b (Sorted)
[26]	Spain	BAT Incineration (35% efficiency)	Variable	High	$12 - 16.9^c$	588^c (BAT Incineration)
		IGCC Gasification (26% net efficiency)				437^c (IGCC Gasification)

Legend: ^a Reported on a dry mass basis for Solid Recovered Fuel (SRF); ^b Values referenced per tonne of raw MSW as-received; ^c Values referenced per tonne of rejects from Materials Recovery Facilities (MRFs); ICE: Internal Combustion Engine; BAT: Best Available Techniques; IGCC: Integrated Gasification Combined Cycle.

Beyond absolute generation metrics, it must be emphasised that maximizing total energy generation is not the primary objective but rather optimizing overall system efficiency. Therefore, the simultaneous diversion of recyclable and organic materials supports MSW management sustainability and circular economy targets while simultaneously enhancing the thermodynamic performance of the WtE facility.

Even with the absolute energy reduction, the social reach remains significant. By adopting the consumption baseline of 2.437 MWh year⁻¹ per household [39], the WtE system in Mexico City could still supply approximately 750,000 residences in the most advanced scenario (SC3.3). In Santo André, even under the most conservative operational scenario ($E_{\text{gen, min}}$ in SC3.3), over 23,000 households would receive continuous baseload electricity, reaching nearly 33,000 households under maximum efficiency conditions ($E_{\text{gen, max}}$).

These findings corroborate the findings of [26], who argued that recycling and energy recovery are complementary rather than mutually exclusive pathways. The empirical data demonstrate that diverting high-calorific dry fraction materials does not "extinguish" WtE feasibility; instead, when combined with organic waste diversion, it stabilizes the thermochemical process by increasing LHV and mitigating moisture-related parasitic heat losses.

Landfill Diversion Rate Estimation

Table 10 presents the percentage of waste mass effectively diverted from landfills across the evaluated scenarios for each municipality.

Table 10. Landfill Diversion Rate (LDR) across management scenarios for the municipalities of Santo André, Mexico City (CDMX), and Guadalajara

Municipality	SC1	SC2.1	SC2.2	SC2.3	SC3.1	SC3.2	SC3.3
Santo André	70.16%	71.98%	73.28%	74.90%	73.07%	74.37%	75.99%
CDMX	76.27%	77.53%	78.96%	80.74%	78.28%	79.71%	81.49%
Guadalajara	69.72%	71.70%	73.31%	75.32%	72.89%	74.50%	76.51%

The Landfill Diversion Rate (LDR), presented in Table 10, serves as the primary metric for assessing the environmental performance of the integrated waste management system. Unlike theoretical models that frequently overlook residual streams, the results obtained for the three municipalities reflect a realistic engineering approach that accounts for bottom and fly ash generation, non-recyclable inert fractions, and operational plant downtime.

In the Baseline Scenario (SC1) — wherein Waste-to-Energy WtE is applied to the current unsorted waste stream — the LDR ranges from 69.72% in Guadalajara to 76.27% in Mexico City. This indicates that the thermal recovery alone could divert nearly three-quarters of the waste mass currently destined for final disposal in landfills.

As waste management strategies progress towards Scenario 3.3, a consistent improvement in diversion efficiency is observed:

- Santo André increases its diversion from 70.16% to 75.99%.
- Guadalajara exhibits the most pronounced growth, rising from 69.72% to 76.51%.
- Mexico City maintains the highest overall performance, reaching an LDR of 81.49%.

The variation in mass reduction diverted from sanitary landfills across Santo André (SA), Mexico City (CDMX), and Guadalajara highlights the decisive influence of municipal gravimetric compositions and baseline waste management infrastructures. Across all three municipalities, the implementation of combined recycling and organic diversion targets drastically compresses the residual fraction destined for final disposal, yielding a remaining landfill flux composed primarily of inert rejects and ash. However, the magnitude of this reduction is most pronounced in Guadalajara, which benefits proportionally the most in percentage terms due to its significantly higher initial organic fraction—noting that its gravimetric profile relies on external secondary data

sources. In such organic-rich contexts, diverting the moisture-heavy putrescible stream removes a substantial portion of the bulk waste mass prior to thermal processing, thereby maximising overall volumetric diversion and optimizing the calorific performance of the remaining combustible fraction. Conversely, in SA, where the baseline gravimetric composition reflects a lower relative proportion of putrescible material, the primary driver for mass reduction shifts toward the recovery of dry recyclables. Ultimately, these municipal disparities demonstrate that while the synergistic 40% recycling and 45% organic diversion framework consistently minimise landfill dependence across all three jurisdictions, the precise mass-reduction efficacy is fundamentally anchored to local waste composition and initial collection dynamics.

These findings demonstrate that the synergy between high recycling rates (40%) and organic waste diversion (45%), not only enhances fuel quality for WtE conversion but also optimises overall mass allocation. The remaining ~20% of the mass routed to landfills consists predominantly of stable, non-combustible materials (ash and inert rejects). This represents a substantial mitigation of environmental liabilities—namely leachate generation and fugitive methane emissions—when compared with baseline 100% landfilling practices, as landfilling untreated biodegradable waste drives long-term anaerobic decomposition, methane release, and leachate contamination [26]. Performance Indicators

To monitor the progress of waste management policies and their alignment with the circular principles, performance indicators were calculated for each scenario based on the metrics established by the Brazilian National Solid Waste Plan (Planares) [8], as shows Table 11. These indices - comprising the Dry Waste Recovery Rate (TR_{rs}), the Organic Waste Recovery Rate (TR_{ro}), and the Integrated Recovery Rate (TR_{rso}) - provide a quantitative measure of material circularity, independent of the energy recovery potential.

Table 11. Performance indicators for material recovery across the evaluated scenarios

Santo André, BR							
Index	SC1	SC2.1	SC2.2	SC2.3	SC3.1	SC3.2	SC3.3
TR_{RSO}		0.08	0.16	0.25	0.13	0.20	0.30
TR_{RS}	Baseline	0.08	0.08	0.08	0.13	0.13	0.13
TR_{RO}		0.00	0.08	0.17	0.00	0.08	0.17
Ciudad de Mexico, MX							
Properties	SC1	SC2.1	SC2.2	SC2.3	SC3.1	SC3.2	SC3.3
TR_{RSO}		0.08	0.17	0.27	0.13	0.22	0.32
TR_{RS}	Baseline	0.08	0.08	0.08	0.13	0.13	0.13
TR_{RO}		0.00	0.09	0.19	0.00	0.09	0.19
Guadalajara, MX							
Properties	SC1	SC2.1	SC2.2	SC2.3	SC3.1	SC3.2	SC3.3
TR_{RSO}		0.08	0.17	0.29	0.12	0.22	0.34
TR_{RS}	Baseline	0.08	0.08	0.08	0.12	0.12	0.12
TR_{RO}		0.00	0.10	0.22	0.00	0.10	0.22

The results for these performance indicators, summarized in Table 11, highlight a clear shift from the current 'zero-recovery' baseline (SC1) to high-performance management configurations. Across all municipalities, the maximum Integrated Recovery Rate (TR_{rso}) is achieved in Scenario 3.3, reaching with values of 0.30 for Santo André, 0.32 for Mexico City, and 0.34 for Guadalajara.

This Progressive increase in material recovery is driven by the organic fraction. While the recovery of dry recyclables (TR_{rs}) remains stable at approximately 12–13% across Scenario 3 (consistent with the targeted 40% diversion of the dry stream), the implementation of source-segregated organic collection significantly enhances overall circularity. In Guadalajara, the TR_{ro}

reaches a peak of 0.22 in SC3.3, reflecting the city's higher organic fraction and underscoring the critical role of biological treatment routes in attaining regional sustainability targets.

Furthermore, the data demonstrates that surpassing an integrated recovery threshold of 30% ($TR_{\text{rso}} > 0.30$) is achievable solely through the synergistic management of both dry and organic waste streams. When combined with energy recovery via thermal processing (mass burning), this high degree of material recovery establishes a robust pathway to drastically reduce landfill dependence and optimize overall resource efficiency across Latin American municipalities.

Ultimately, these findings provide a quantitative validation for the ambitious targets set by Planares 2040 [8]. The capacity of Scenario 3.3 to divert most of the municipal waste away from final disposal sites—through an integrated approach combining recycling, composting, and mass burning—represents a key step toward a sustainable waste management paradigm in Latin America. Except for Mexico City's elevated generation rates, which are inherently tied to its status as a megacity, the observed per-capita waste generation profiles align closely with broader regional Latin American patterns.

Limitations and Uncertainty Considerations

Several methodological assumptions warrant discussion regarding their potential influence on the modelling results. First, due to the scarcity of primary data for Mexico City (CDMX) and Guadalajara, the use of experimental moisture and ash content data from Santo André as a reference for the Mexican municipalities introduces uncertainty into the Lower Heating Value (LHV) estimates. This limitation becomes evident when comparing the data used with the average moisture content of MSW in Mexico City [40]—determined to be 33.7% through fieldwork—a figure notably lower than the value adopted in this study. Using a lower moisture content would further increase the estimated LHV, reinforcing—rather than invalidating—the study's central conclusion: that diverting organic waste effectively stabilises and improves fuel quality.

Second, holding the annual operating time fixed at 8,000 hours and assuming a constant thermal-to-electrical conversion efficiency (within the typical 25–35% range for mass-burn WtE plants) represent operational simplifications. Real-world facility performance is inevitably influenced by maintenance downtime, feedstock heterogeneity, and equipment ageing; thus, the projected energy generation and social-reach metrics should be interpreted as technical recovery potentials rather than guaranteed operational outputs.

Third, the predefined recycling and organic-diversion rates defining the seven scenarios represent discrete policy targets rather than a continuous sensitivity space. Given the linear structure of the underlying mass balance, intermediate values between the modelled scenarios would be expected to yield proportionally intermediate results.

Future Research Directions

To build upon these findings and address the acknowledged limitations, future research would focus on the following avenues would be desirable:

- Primary experimental characterisation: Prioritise extensive sampling and laboratory testing of MSW to establish site-specific proximate and ultimate analyses, thereby reducing proxy-related uncertainties in energy projections.
- Quantitative sensitivity and scenario analysis: a comprehensive quantitative sensitivity analysis varying moisture content, conversion efficiencies, parasitic loads, and plant availability factors to generate probabilistic energy yield distributions.
- Techno-Economic and Life Cycle Assessment (LCA): Integrate detailed capital (CAPEX) and operational (OPEX) cost evaluations with full Life Cycle Assessments to compare the environmental impacts (e.g., carbon footprint,

acidification) of thermal WtE against anaerobic digestion and enhanced material recycling under Latin American market conditions.

- Logistical and Seasonal Dynamics: Evaluate the seasonal variations in waste generation and composition, as well as the spatial collection logistics required to realistically achieve the 40% recycling and 45% organic diversion targets in high-density megacities.

CONCLUSIONS

This study provided a comprehensive comparative analysis of the energy recovery potential from municipal solid waste (MSW) across three municipalities representative urban scales in Brazil and Mexico: Santo André (Brazil), Mexico City, and Guadalajara (Mexico). By modelling seven progressive management scenarios, this research demonstrated that ambitious material circularity targets and thermal energy recovery are not competing strategies but rather synergistic components of a sustainable waste management framework.

The results confirm that while the most optimistic projections for dry waste recycling (40%) and organic waste diversion (45%) lead to a net reduction in total waste mass available for combustion, the thermodynamic properties of the remaining fuel stream improve substantially. Dynamic recalculation of the weighted average moisture demonstrated that diverting organic matter acts as a critical corrective mechanism, elevating the LHV to levels that ensure self-sustained combustion (exceeding 7.0 MJ/kg in CDMX and Santo André).

From an environmental perspective, the integrated management approach (Scenario 3.3) demonstrated exceptional effectiveness, achieving Landfill Diversion Rates (LDR) between 75.99% and 81.49%. This shift redefines sanitary landfills to a strictly residual role—destined primarily for inert materials and process ash—thereby drastically mitigating long-term liabilities such as leachate generation and fugitive methane emissions.

From an energy perspective, higher recycling rates preserved overall system efficacy. Based on the baseline household electricity consumption of 2.437 MWh year⁻¹[39], the energy recoverable in Mexico City alone could power approximately 750,000 households, while in Santo André, nearly 33,000 households could be supplied without reliance on fossil-fuel energy sources. These figures represent the technical ceiling achievable under full-scale WtE deployment; realising this prospective potential will depend on overcoming financial, regulatory, and siting barriers across all three municipalities.

The central scientific contribution of this study lies in demonstrating—backed by primary experimental data rather than generic literature assumptions—that the loss of high-calorific dry recyclables and the removal of moisture via organic diversion function as offsetting mechanisms regarding MSW LHV, firmly validating the hypothesis that material recycling and energy recovery are mutually reinforcing. While prior assessments have examined these drivers in isolation, this work is, to the authors' knowledge, the first to jointly model their dynamic interaction across multiple Latin American urban contexts using a Material Flow Analysis coupled with an adaptively recalculated LHV.

Beyond its immediate empirical findings for Santo André, Mexico City, and Guadalajara, the methodological framework developed herein is highly transferable to other cities across the Global South experiencing similar data constraints. Replicating this approach requires, at minimum, local gravimetric composition profiles and proximate analysis metrics for major combustible fractions; where such experimental data are lacking, the validated regional proxy methodology established here offers a robust, practical alternative. Consequently, this framework serves as a strategic decision-support tool for municipal policymakers in evaluating whether—and under which precise recycling and organic diversion targets—thermal WtE infrastructure is technically and environmentally justified before committing capital investment.

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This section lists the abbreviations and symbols used throughout the manuscript.

Abbreviations

ABREMA	Brazilian Association of Wastes an Environment (Associação Brasileira de Resíduos e Meio Ambiente)
BAT	Best Available Techniques
CDMX	Mexico City (Ciudad de México)
EPR	Extended Producer Responsibility
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
ICE	Internal Combustion Engine
IGCC	Integrated Gasification Combined Cycle
INEGI	National Institute of Statistic and Geography (Instituto Nacional de Estadística y Geografía - Mexico)
LAC	Latin America and the Caribbean
LDR	Landfill Diversion Rate (%)
LHV	Lower Heating Value (MJ kg ⁻¹)
LHV _{wb}	Lower Heating Value wet basis
MFA	Material flow analysis
MRF	Materials Recovery Facility
MSW	Municipal Solid Waste
OECD	Organisation for Economic Co-operation and Development
PLANARES	Brazilian National Solid Waste Plan (Plano Nacional de Resíduos Sólidos)
PNRS	Brazilian National Solid Waste Policy (Política Nacional de Resíduos Sólidos)
RDO	Recovery Rate of Organic Waste (%)
RDR	Recovery Rate of Dry Recyclables
RSU	Municipal Solid Waste (Resíduos Sólidos Urbanos)
SA	Santo André
SC	Scenario (SC1, SC2, SC3)
SD	Slowly degradable material
SNISA/SNIS	National Basic Sanitation Information System (Sistema Nacional de Informações sobre Saneamento Básico - Brazil)
SRF	Solid Recovered Fuel
TR _{ro}	Mass Recovery Rate of Organic Waste (%)

TRrso	Integrated Recovery Rate (%)
TDland	Landfill Diversion Rate (%)
WtE	Waste-to-Energy

Symbols

AC _{f,k}	Ash content of combustible waste fraction k (% dry basis)
E _e	Thermal-to-electrical transformation efficiency (%)
E _g	Theoretical annual electrical energy generated
E _{g,total}	Net annual electrical energy effectively generated (MWh year ⁻¹)
LHV _{wb}	Lower Heating Value on a wet basis
MSW _{fuel}	Total annual mass of MSW fuel fractions destined for WtE (t year ⁻¹)
MSW _j	Initial total mass of waste fraction j (t)
MSW _{of}	Initial total mass of organic waste (t)
MSW _{landfill}	Total mass of waste directed to sanitary landfills (t year ⁻¹)
MSW _{rf,i}	Initial total mass of dry recyclable fraction i (t)
MSW _{rof}	Total recovered mass of organic waste (t)
MSW _{rrf,i}	Recovered mass of dry recyclable fraction i (t)
N _{res}	Equivalent serviced residences (households)
O _r	Mass fraction of organic waste (gravimetric fraction, wet basis)
P _a	Mass fraction of paper/cardboard waste (gravimetric fraction, wet basis)
P _i	Plastic Mass fraction of plastic waste (gravimetric fraction, wet basis)
S _a	Mass fraction of sanitary waste (gravimetric fraction, wet basis)
T	Mass fraction of textile waste (gravimetric fraction, wet basis)
UnMSW _j	Remaining unrecovered mass of waste fraction j (t)
UnMSW _{f,k}	Unrecovered mass of combustible waste fraction k (t)
W	Weighted average moisture content (gravimetric fraction or %)
W _k	Moisture content of combustible waste fraction k (gravimetric fraction)

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