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Review

A Review of Organic Municipal Waste Management in Medium Cities in Latin America

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Abstract

Latin America faces growing challenges in the management of municipal solid waste (MSW). This is particularly evident in medium-sized and metropolitan cities where rapid urbanization, limited infrastructure, and high proportions of organic waste (40–70%) converge. This review synthesizes the most recent advances in organic waste management, valorization strategies, environmental performance, and policy frameworks in Mexico and Latin America. To provide a comprehensive overview, evidence from studies on informal recycling systems, route optimization, sustainable landfill siting, food waste valorization, life cycle assessments (LCAs), and biogas production is integrated. Techno-economic analyses of energy recovery from organic fractions are specifically reviewed. This review highlights that valorization of organic waste through composting, anaerobic digestion, food supplementation, and bioproduct generation can reduce greenhouse gas emissions by 40–70% compared to landfilling, with AD–composting hybrids achieving the highest reductions of 60–70%. Community composting achieved moderate reductions, 30–50%, but at significantly lower cost and with greater social co-benefits. These alternatives for valorizing the organic fraction extend the lifespan of both confined and open landfills. It also contributes to mitigating the public health impacts related to open dumping, disease vectors, and contaminated leachate. In short, this review also highlights shortcomings in policy coherence, financial mechanisms, source separation, and technology adoption. A strategic framework is proposed that prioritizes decentralized treatment systems, the integration of informal recyclers, tax incentives, community-based waste separation, and planning based on Life Cycle Assessment (LCA). The findings point to a viable strategy for transitioning from landfill dependency to circular waste management systems that improve the quality of life for the population of Latin America and the Caribbean.

Keywords: organic municipal waste; Latin America; waste valorization; anaerobic digestion; composting; circular economy; landfill sustainability; environmental impact; LCA

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1. Introduction

The rapid and unplanned urbanization process that defines Latin America and the Caribbean (LAC) presents a critical dual challenge. This challenge is to promote sustainable development for a rapidly growing urban population while simultaneously managing the increasing volumes of municipal solid waste (MSW) generated by this process [1]. In

Latin America and the Caribbean (LAC), more than 80% of the population lives in cities. This creates unique waste management pressures that intersect with socio-economic inequalities and environmental vulnerabilities [2]. LAC generates approximately 231 million tons of MSW per year. This MSW generation presents per capita rates in metropolitan areas comparable to those of developed nations [3]. This places enormous pressure on existing collection, treatment, and disposal systems in LAC countries. Within this waste stream, the organic fraction (FMSW) constitutes between 50% and 60% of the total MSW composition [4]. FMSW covers food waste, garden clippings, and other biodegradable materials, as shown in Table 1.

Table 1. Comparative municipal solid waste generation and organic fraction composition across selected Latin American countries.

Country	Population (millions)	Urban Population (%)	Total MSW Generation (million tons/year)	Per Capita MSW Generation (kg/person/day)	Organic Fraction (% of Total MSW)	Data Year
Brazil	213	87%	79	1.04	51% (range: 45–60%)	2020
Mexico	128	81%	53.1	1.14	53% (range: 47–71%)	2020
Colombia	51	81%	32.3	1.72	62% (range: 55–68%)	2019
Argentina	45	92%	17.9	1.09	55% (range: 50–62%)	2020
Chile	19	88%	8.2	1.19	58% (range: 52–64%)	2021
Peru	33	78%	8.8	0.73	58% (range: 52–65%)	2019
Ecuador	18	64%	5.3	0.81	61% (range: 56–67%)	2020
LAC Regional Average	~650	81%	~231	0.99	54%	2018
OECD Average	—	—	—	1.4	34%	2018
Global Average	—	—	—	0.74	44%	2018

Note: Data compiled from national reports and peer-reviewed studies; ranges reflect variation across cities and regions within each country [3,4].

This high percentage of the organic fraction is a significant untapped resource within a circular economy paradigm. Valorizing this organic fraction is essential for sustainable urban futures [5]. Waste management systems prevalent in many medium and large cities in Latin America and the Caribbean (LAC) remain rooted in a linear model. This model generates a strong dependence on landfill disposal and a persistent prevalence of uncontrolled dumpsites [6]. It is estimated that almost 40% of the MSW collected in the region is still deposited in environmentally unsanitary sites, a practice that leads to serious environmental and public health impacts [7]. These impacts include the generation of greenhouse gases (GHGs), such as methane, produced by the anaerobic decomposition of organic waste. The decomposition of organic waste itself generates leachate that contaminates surface and groundwater. These environmental impacts also present a latent risk to public health [8]. Conventional disposal of OFMSW generates these negative environmental impacts, making comprehensive treatment a critical environmental and climate mitigation priority [9]. Conversely, targeted management of OFMSW through separate collection and biological treatment is recognized as a fundamental strategy for reducing its generation. Furthermore, it reduces dependence on landfills, mitigates GHG emissions, and recovers valuable resources [10].

The concept of valorization extends beyond conventional treatment. This concept aims to restore economic and ecological value to waste streams by reintegrating them into production and consumption cycles [11]. For OFMSW, valorization can be achieved through biological processes such as anaerobic digestion (AD), composting, and emerging thermochemical alternatives [12]. AD technology offers the dual benefit of producing biogas (a renewable energy source) and nutrient-rich digestate (a soil amendment). This technology contributes to both energy security and agricultural sustainability [13]. Composting is a widely adopted technology for transforming OFMSW into stable organic matter. Compost products can be used as a soil remediator and reduce dependence on chemical fertilizers in regions with significant agricultural activity [14]. Furthermore, this process can be used to sequester atmospheric carbon and reduce greenhouse gas (GHG) emissions. However, the successful implementation and scaling up of these technologies in Latin America and the Caribbean (LAC) depend on technical feasibility, regional public policies, and economic and social factors [15]. The main barriers include fragmented regulatory frameworks, limited financial investment, and an incipient market for recovered products. In addition, the low rate of citizen participation in source separation and the large informal waste picker sector in the value chains are barriers to reducing OFMSW in LAC [16,17].

A comprehensive assessment of the sustainability of OFMSW recovery systems should employ a holistic framework that rigorously balances environmental, economic, and social dimensions [18]. An effective system should demonstrate a positive net environmental footprint using tools such as Life Cycle Assessment (LCA). Achieving long-term economic viability is a challenge that can be met through business and financing models adapted to the region's social and political realities [19]. These new models should promote social inclusion and equity to generate sustainable development. The social dimension is especially relevant in the context of LAC, where the informal sector carries out a substantial portion of collection and recycling activities. Therefore, inclusive policies that offer fair working conditions to waste pickers are an ethical imperative and a prerequisite for the system's efficiency and legitimacy [20].

Currently, a large amount of research on waste management in the Latin America and Caribbean (LAC) region has been reported in the literature. However, there is a pressing need for a comprehensive review that critically and impartially examines the interconnected pillars of solid waste management, technological recovery, and multidimensional sustainability. This review focuses directly on municipal solid waste (MSW) in medium-sized and metropolitan cities in Latin America and the Caribbean [21]. This review offers an updated, comprehensive analysis of the challenges of MSW management in the region, identifying key drivers and systemic barriers [22]. It also presents a systematic review of applicable recovery technologies, assessing their readiness, performance, and contextual suitability for urban environments in LAC [23]. Finally, it proposes an integrated framework that evaluates the sustainability of recovery pathways for the organic waste fraction. Furthermore, it analyzes the enabling policy instruments, economic mechanisms, and participatory governance models necessary for a transition to a circular economy for organic waste [24]. This work aims to provide information based on technical and scientific evidence so that policymakers, urban planners, and stakeholders can make municipal solid waste of organic origin a priority in sustainable and resilient urban development in LCA [25].

2. Systematic Literature Review Approach

Given the inherent risk of bias and lack of reproducibility in traditional narrative reviews, this study adopted a systematic literature review methodology to ensure transparency, rigor, and comprehensiveness in synthesizing the available evidence on organic municipal solid waste (OMSW) valorization in Latin American cities [22,23]. The review protocol was designed following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to structure the search, selection, and synthesis processes [24].

2.1. Research Questions

The review was guided by the following primary research questions:

1. What are the documented generation rates, compositional characteristics, and data reliability issues concerning OMSW in medium-sized and metropolitan Latin America cities?
2. What valorization technologies (composting, anaerobic digestion, thermochemical processes, and biorefineries) have been applied or studied in the region, and what is their reported performance, readiness level, and contextual suitability?
3. What environmental, economic, and social outcomes have been associated with different OMSW management strategies, as assessed through Life Cycle Assessment (LCA) and other sustainability evaluation tools?
4. What are the main policy frameworks, governance structures, and barriers influencing the implementation of circular economy approaches for OMSW in the region?

2.2. Search Strategy and Databases

A comprehensive literature search was conducted in December 2024 and updated in January 2025 across four major scientific databases: Scopus, Web of Science, ScienceDirect, and Google Scholar. These databases were selected to ensure coverage of both peer-reviewed academic literature and relevant grey literature (technical reports, conference proceedings, and policy documents) from Latin American sources. The search strategy combined Boolean operators with keywords related to: (i) geographic scope ("Latin America," "Mexico," "Brazil," "Colombia," "Chile," "Argentina," "Caribbean," "medium-sized cities," and "metropolitan areas"); (ii) waste stream ("organic waste," "food waste," "garden waste," "municipal solid waste," "OFMSW," and "biowaste"); (iii) valorization pathways ("composting," "anaerobic digestion," "biogas," "waste-to-energy," "biorefinery," and "circular economy"); and (iv) assessment methods ("life cycle assessment," "LCA," "techno-economic analysis," "sustainability assessment," and "social inclusion").

2.3. Inclusion and Exclusion Criteria

Studies were included if they met the following criteria: (i) focused on municipal organic waste (food waste, yard waste, or the organic fraction of MSW); (ii) provided original data, case studies, or comprehensive reviews relevant to Latin American and Caribbean contexts; (iii) addressed at least one aspect of waste characterization, technological valorization, sustainability assessment, or policy analysis; (iv) were published between 2015 and 2025 to capture recent developments while allowing inclusion of foundational policy documents; and (v) were written in English, Spanish, or Portuguese to encompass regional scientific output.

Exclusion criteria were: (i) studies focused exclusively on industrial, agricultural, or non-municipal organic waste streams without clear relevance to urban waste management; (ii) opinion pieces, editorials, or non-peer-reviewed conference abstracts without

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substantive data; and (iii) studies from countries outside the LAC region, unless they provided direct comparative insights applicable to Latin American contexts.

2.4. Screening and Selection Process

The initial database search yielded 1847 potentially relevant records. After removing duplicates (n = 423), 1424 records underwent title and abstract screening by two independent reviewers (LYPM and AGL) based on the inclusion criteria. Disagreements were resolved through consensus or consultation with a third reviewer (JEBA). Full-text assessment was conducted for 312 articles, of which 142 were included in the final synthesis. The primary reasons for exclusion at the full-text stage were lack of specific focus on organic municipal waste (n = 58), absence of primary data or rigorous analysis (n = 42), geographic scope outside LAC without transferable insights (n = 24), and redundancy with more comprehensive studies on the same topic (n = 15). The reference list of included studies was also hand-searched to identify additional relevant publications.

2.5. Data Extraction and Synthesis

A standardized data extraction form was developed to capture bibliographic information, geographic focus, study objectives, waste characterization data, technologies assessed, sustainability evaluation methods (LCA, TEA, and social analysis), key findings, and reported barriers or opportunities. Given the heterogeneity of study designs, outcome measures, and contextual factors, a narrative synthesis approach was adopted, organizing findings thematically according to the research questions. Where possible, quantitative data on generation rates, GHG reduction potentials, and economic parameters were extracted and tabulated to enable cross-study comparison. The quality of included studies was assessed using adapted criteria based on study design, methodological rigor, and relevance to the regional context, though no studies were excluded based solely on quality to ensure comprehensive coverage of the nascent literature in this field.

3. Organic Municipal Waste in Latin America: Quantification and Characteristics

Accurate quantification and detailed characterization of the Organic Fraction of Municipal Solid Waste (MSW) are fundamental requirements for designing effective management and recovery systems. In the context of LCA, this data is crucial for assessing the magnitude of the resource recovery opportunity, planning appropriate treatment infrastructure, and formulating evidence-based policies. This section summarizes the current state of knowledge on MSW generation rates, compositional characteristics, and data reliability in urban centers of the region.

3.1. Generation Rates and Dominance in Waste Stream

The most striking characteristic of municipal solid waste (MSW) in Latin America is the high proportion of biodegradable organic material. Studies across the region consistently identify the organic fraction as the largest component of the urban waste stream [26]. Recent analyses corroborate that organic matter of mineral waste (OFMW) typically constitutes between 50% and 60% of the total MSW generated by weight in most cities in Latin America and the Caribbean, as shown in Figure 1. This figure is significantly higher than the global average and substantially higher than the levels observed in developed economies. In developed nations, inorganic materials such as food containers and packaging predominate [27]. This high organic content is directly linked to dietary habits and climate (which favors the production of perishable fruits and vegetables). It is also a consequence of lower levels of industrialization and lower consumption of processed products compared to developed nations.

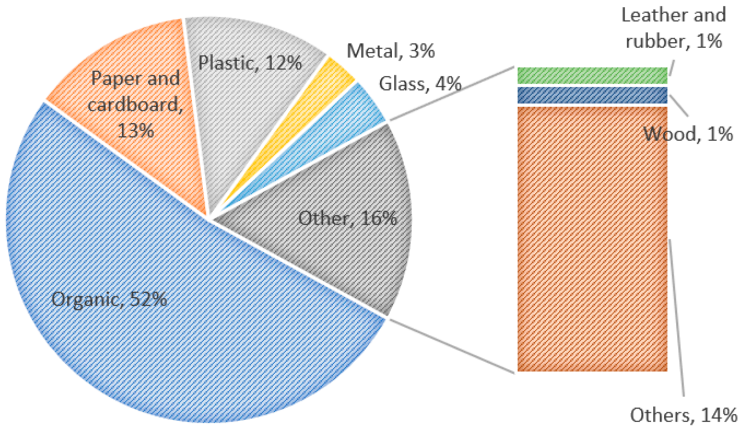

Figure 1. Classification of municipal solid waste (MSW) by area and percentage by weight, estimated for a medium-sized city in the Latin America and Caribbean (LAC) region. Source: Compiled from [4,26,27] with data years (2018–2022) specified.

Quantifying the absolute generation of OFMSW requires understanding both its proportional contribution and the total per capita MSW generation rate. While total MSW generation in Latin America and the Caribbean (LAC) averages approximately 0.5 to 1.1 kg/person/day, this figure is lower than in high-income countries. The high proportion of organics results in a high flow of biodegradable waste per day. For a metropolitan city of 10 million inhabitants, this translates to more than 3000 tons of organic waste produced daily. This amount of OFMSW poses an enormous waste management challenge but also represents a massive raw material for circular economy initiatives [28]. It is crucial to note that generation rates are not static and show a positive correlation with income levels. As economic development progresses in parts of LAC, per capita waste generation is increasing. This is causing the composition of the waste to slowly evolve, with a growing proportion of plastics and other non-organic materials. However, the organic fraction remains persistently dominant. The above underlines the long-term relevance of OFMSW-focused strategies [29].

3.2. Compositional Characteristics and Variability

The term "municipal organic waste" refers to a heterogeneous mixture of materials with diverse physicochemical properties. These physicochemical properties are a predominant factor in choosing the recovery process. The main components are:

- Food waste: This sub-fraction is the most representative and includes raw food scraps, spoiled products, leftover dishes, and food processing waste. It is characterized by a high moisture content (70 to 85%), high biodegradability, and a carbon-to-nitrogen (C/N) ratio optimal for biological processes.
- Garden waste: This includes grass clippings, leaves, branches, and other gardening debris. Its composition is primarily lignocellulosic, with a higher C/N ratio and lower moisture content. Seasonality significantly influences the generation of this type of organic waste.
- Other biodegradable materials: This category may include small amounts of paper, cardboard, and natural textiles.

The specific composition of municipal organic waste is not uniform throughout the region. This composition varies significantly according to factors such as climate zone, socio-economic level, cultural habits, and degree of urbanization [30,31]. As shown in Figure 2, the percentage of organic fraction in municipal solid waste (MSW) is illustrated based on the economic region in Mexico.

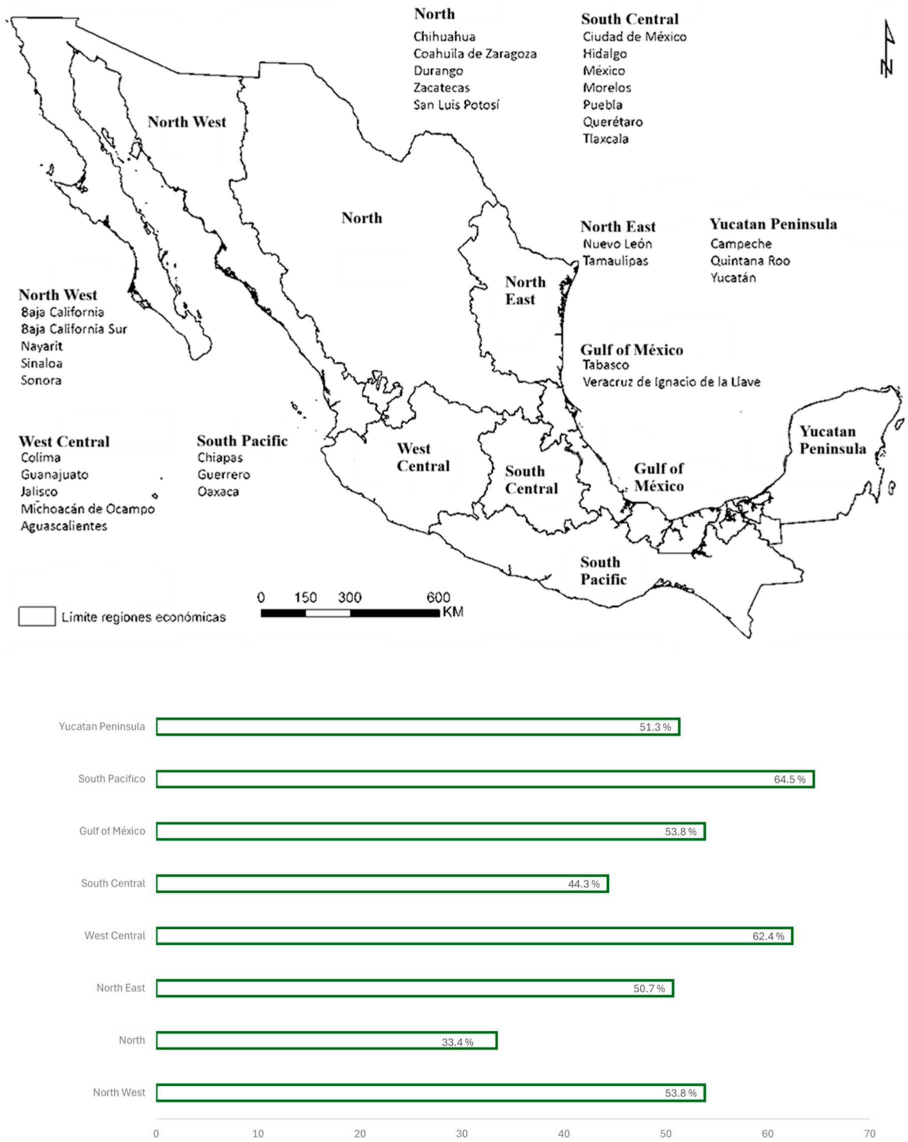

Figure 2. Percentage of organic fraction in municipal solid waste (OFMSW) per economic region in Mexico. Data from Rueda-Avellaneda et al. 2021 [31]. Source and sample period (2016–2020).

For example, cities in tropical and subtropical zones with a strong agricultural sector tend to have a higher proportion of fruit and vegetable waste. Conversely, in more temperate or affluent urban areas, the proportion of garden waste and prepared food scraps may be higher. Detailed characterization, such as moisture content, bulk density, C/N ratio, and potential contaminant levels, allows for the determination of key parameters for waste valorization. This is confirmed in the case of waste streams with very high moisture content, which may be more suitable for wet anaerobic digestion than for composting.

3.3. Critical Data Gaps and Methodological Challenges

One of the barriers to effective planning in Latin America and the Caribbean (LAC) is the scarcity of reliable, standardized, and up-to-date data on waste quantification and characterization. National statistics and reports from municipal authorities exist, but they often have several limitations, as shown below [32]:

- Methodological inconsistency: Waste characterization studies are conducted using different methodologies and sampling periods, and they do not take into account seasonal variations or definitions of waste categories. This makes comparisons between cities or countries difficult.

- Incomplete coverage: Many studies focus solely on the formal waste collection system. This omits large quantities of waste managed by the informal sector, deposited in illegal dumps, or not collected at all. These quantities of OFMSW that are not considered in the quantification are concentrated especially in peri-urban and low-income areas. This leads to a systematic underestimation of total waste generation.
- Lack of regular monitoring: Waste characterization is often a one-off project rather than a routine and institutionalized monitoring activity. As a direct consequence, data quickly becomes outdated because it fails to capture evolving consumption patterns and waste flows.
- Underreporting of food waste: Obtaining accurate data on household food waste is particularly difficult. Therefore, this data relies on rough estimates.

These data gaps contribute to the inadequate design of treatment facilities. This is because the size or specifications are often based on inaccurate assumptions about raw materials. The consequence of this poor information quality is operational inefficiencies or failures. Investment in standardized, periodic, and transparent waste characterization programs is a fundamental research and policy need to promote sustainable waste management in Latin America and the Caribbean [33].

3.4. The Food Waste Imperative

Within the OFMSW stream, special attention must be paid to food waste. Recent global and regional initiatives have highlighted the reduction in and valorization of food waste as critical to achieving food security, climate goals, and resource efficiency. In LAC, a significant portion of food waste occurs at the consumption stage (households, restaurants, and markets), but losses also occur along the supply chain due to infrastructural deficiencies in storage, transport, and processing [34]. Quantifying this flow is complex but vital. Studies focusing on urban food waste suggest it can represent 30–50% of the total OFMSW, making it the single largest, most energy-rich, and most readily biodegradable component [35]. Its high moisture and nutrient content make it an excellent substrate for anaerobic digestion, while its sheer volume necessitates dedicated prevention and management strategies aligned with Sustainable Development Goal 12.3.

3.5. Regional and Socio-Economic Disparities

Finally, the quantification and characteristics of OFMSW are not homogeneous within countries or even within single cities. There is a clear socio-economic gradient. Higher-income neighborhoods typically generate more waste per capita, with a composition that includes more packaging, electronics, and garden waste. Lower-income neighborhoods often generate less total waste per capita, but the organic fraction tends to be an even higher percentage of their waste stream, sometimes exceeding 70%, as consumption of packaged goods is lower [36]. Furthermore, medium-sized cities may face different challenges than megacities; while the total volumes are smaller, they often have more limited technical and financial capacities for conducting characterization studies and implementing sophisticated valorization schemes [37].

In conclusion, the organic fraction is the defining component of municipal waste in Latin American cities, representing both the core of the disposal challenge and the heart of the valorization opportunity. While its general dominance is well-established, critical work remains in standardizing measurement, improving the resolution and frequency of characterization data, and understanding sub-streams like food waste. Reliable data is the

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indispensable foundation upon which effective, tailored, and sustainable revalorization systems must be built for the diverse urban landscapes of the region.

4. Management Frameworks and Strategic Approaches

In Latin America, the management of organic municipal waste (OMW) in medium-sized cities represents both a critical challenge and a strategic opportunity for advancing urban sustainability. Cities in Mexico, Colombia, and Brazil share structural conditions such as accelerated urbanization, limited municipal budgets, institutional fragmentation, and a high organic fraction in municipal solid waste streams. These characteristics require management frameworks that are flexible, context-sensitive, and aligned with circular economy principles. In medium-sized cities, where governance capacities are often more constrained than in large metropolitan areas, integrated management frameworks play a decisive role. Circular economy-oriented strategies emphasize source separation of organic waste, decentralized treatment systems, and local valorization pathways, such as composting and anaerobic digestion, that can be adapted to local agricultural, energy, and labor contexts [38]. In Mexico and Colombia, these approaches are particularly relevant for peri-urban areas where organic waste valorization can be linked to soil restoration and small-scale energy generation.

Strategic approaches such as Integrated Sustainable Waste Management (ISWM) and adaptive governance models have been identified as effective tools for addressing systemic inefficiencies in Latin American cities. These frameworks promote coordination among municipal governments, private service providers, community-based organizations, and informal actors who continue to play a significant role in waste management systems in the region [39]. In Brazil, where municipal autonomy is relatively strong, cities that adopt participatory and multi-actor governance structures tend to show greater progress in implementing organic waste valorization initiatives. Institutional capacity and policy coherence are key enabling factors across the region. Medium-sized cities with clear regulatory frameworks, stable financing mechanisms, and technical expertise are more likely to move beyond waste disposal practices toward recovery-based systems. Strategic roadmaps aligned with national climate commitments and sustainability agendas (such as waste diversion targets and greenhouse gas mitigation targets) also improve access to finance and technical cooperation on the path to generating a circular economy [40], as shown in Figure 3.

Figure 3. Summary of key circular economy policy measures. Schröder et al. 2025 [40].

Finally, effective management frameworks must incorporate monitoring and evaluation mechanisms to ensure continuous improvement. The use of performance indicators, life cycle assessment, and data-driven decision-making supports adaptive management and helps municipalities refine strategies in response to operational and socio-economic constraints. Overall, the literature indicates that the success of OMW revalorization in medium-sized cities of Mexico, Colombia, and Brazil depends not only on technological solutions, but also on robust management frameworks and strategic approaches that integrate governance, social inclusion, and circular economy objectives [41].

4.1. Core Principles of Integrated Waste Management

Effective Integrated Waste Management (IWM) constitutes a foundational framework for advancing the revalorization of organic municipal waste (OMW) in Latin America and the Caribbean. The region is characterized by rapid urban growth, pronounced socioeconomic inequalities, institutional fragmentation, and a consistently high proportion of organic matter within municipal solid waste streams. In this context, IWM provides a systemic approach that integrates technical solutions, governance arrangements, financial mechanisms, and social participation to optimize waste flows across the entire management chain. In LAC cities, particularly medium-sized and emerging metropolitan areas, waste management systems have historically prioritized collection and final disposal, often relying on landfills with limited environmental controls. IWM challenges this paradigm by promoting waste prevention, source separation, recovery, and valorization as interdependent components of a unified system [42]. This holistic perspective is especially relevant for organic waste, which represents both the largest waste fraction and the greatest opportunity for circular economy implementation in the region. A core principle of IWM is the alignment of waste management strategies with local urban, economic, and environmental conditions. In Latin America and the Caribbean, decentralized and modular systems have gained attention due to their adaptability to heterogeneous urban morphologies and variable institutional capacities. Composting, anaerobic digestion, and hybrid treatment schemes are increasingly integrated into municipal strategies as complementary rather than competing solutions [43]. These approaches enable cities to reduce landfill dependency while generating valuable outputs such as soil amendments, biogas, and biofertilizers.

Governance plays a decisive role in the operationalization of IWM frameworks. Multilevel coordination among national authorities, municipalities, private operators, and civil society organizations is essential to overcome institutional silos that traditionally hinder waste valorization initiatives. Studies emphasize that successful IWM systems in LAC often rely on enabling regulatory frameworks that clearly define responsibilities, establish technical standards, and incentivize organic waste recovery through economic instruments [44]. In this regard, policy coherence across environmental, energy, and agricultural sectors is particularly important for scaling organic waste valorization pathways.

Social inclusion is another critical dimension of IWM in Latin America and the Caribbean. Informal actors continue to play a significant role in waste management systems, especially in collection and material recovery stages. Integrated frameworks increasingly recognize the need to incorporate these actors into formal systems through cooperative models, capacity-building programs, and inclusive governance mechanisms [45]. Although informal participation is less pronounced in the management of organic waste compared to recyclables (metals, paper, cardboard, and plastics), community-based composting initiatives demonstrate the potential of participatory approaches to improve system performance and social acceptance, as in the case of Brazil [43].

From a strategic planning perspective, IWM emphasizes the use of analytical tools to support evidence-based decision-making. Life cycle assessment (LCA), material flow analysis (MFA), and scenario modeling are widely recommended to evaluate the environmental, economic, and social impacts of alternative management options [46]. In the context of LAC cities, these tools are particularly valuable for identifying trade-offs between centralized and decentralized treatment systems, as well as for prioritizing investments under constrained financial conditions.

Financial sustainability remains a persistent challenge for IWM implementation in the region. Integrated frameworks highlight the importance of diversified funding mechanisms, including municipal budgets, user fees, public–private partnerships, and international climate finance [47]. Organic waste valorization projects that demonstrate co-benefits, such as greenhouse gas mitigation, renewable energy generation, and soil restoration, are increasingly positioned to access green financing instruments, thereby strengthening the economic viability of IWM systems.

Capacity-building and institutional learning are also central to the long-term success of IWM. Medium-sized cities in Latin America and the Caribbean often face technical and managerial capacity gaps that limit the effective operation of integrated systems. Continuous training programs, knowledge exchange networks, and regional cooperation platforms are identified as key enablers for strengthening local capacities and fostering innovation [48]. These mechanisms support the adaptation of international best practices to local realities rather than their direct replication.

Finally, monitoring and evaluation mechanisms are essential components of IWM frameworks. The use of performance indicators related to waste diversion rates, organic waste recovery efficiency, greenhouse gas emissions, and socio-economic outcomes enables municipalities to track progress and adjust strategies over time [49]. Digitalization and data-driven management tools are emerging as valuable assets for improving transparency and accountability in waste management systems across the region.

4.2. Circular Economy as a Unifying Paradigm

The transition from linear disposal models to circular economy (CE) principles represents a fundamental paradigm shift essential for sustainable urban development in Latin America and the Caribbean. Within this framework, Integrated Waste Management (IWM) provides an operational architecture to implement CE concepts at the city level, combining technical solutions—such as source separation, decentralized treatment facilities, and market development for end-products—with governance innovation, social inclusion, and strategic planning [50–59].

This system's perspective redefines organic municipal solid waste (OFMSW) from a disposal problem into valuable biological nutrients and energy flows. For medium-sized and metropolitan cities in LAC, this integration is not merely a technical upgrade but a systemic transformation linking urban metabolism with climate action, resource security, and soil restoration [57,58]. The CE hierarchy prioritizes prevention, followed by nutrient and energy recovery through anaerobic digestion and composting—directly contrasting with landfill-dependent models that generate methane emissions and dissipate resources. However, successful implementation depends on sustained political commitment, institutional capacity, and context-sensitive design reflecting the diverse realities of cities across the region [58,59].

The policy context for CE and OFMSW valorization in LAC is characterized by a patchwork of advancing national frameworks and persistent implementation gaps. Several countries have enacted overarching waste management or CE laws. For instance, Chile's Extended Producer Responsibility (EPR) Law (2016) and Colombia's National Circular Economy Strategy (2019) establish ambitious targets for landfill diversion and material recovery [60]. Similarly, Brazil's National Solid Waste Policy (PNRS) of 2010 legally mandates the gradual elimination of dumps and promotes reverse logistics and recycling cooperatives [51]. However, the specific regulatory and economic instruments to drive OFMSW valorization are often underdeveloped. Key policy mechanisms include:

- Landfill Bans and Diversion Targets: Mandates that prohibit the landfilling of untreated organic waste after a certain date are powerful drivers for investment in treatment infrastructure, as seen in the European Union and increasingly contemplated in LAC metropolitan plans [61].
- Economic Instruments: These include landfill taxes (to make disposal less economically attractive), pay-as-you-throw schemes (to incentivize waste reduction at source), and subsidies or feed-in tariffs for energy generated from biogas [62]. Their application in LAC remains limited and uneven.
- Public Procurement Policies: Governments can stimulate markets for compost and digestate by mandating or prioritizing their use in public parks, road verges, and agricultural projects, ensuring a reliable demand for circular products [63].

A critical and distinctive feature of the LAC context is the central role of the informal waste sector, primarily waste pickers. A socially inclusive CE transition necessitates policies that formally integrate these actors into the OFMSW value chain. Successful models, such as Colombia's Law 511 of 2021, which recognizes waste pickers as public service providers, or Brazil's support for recycling cooperatives within the PNRS, demonstrate that formalization, fair remuneration, and access to social security are not only ethical imperatives but also enhance system efficiency and collection rates [64]. Excluding this vast workforce from formal CE policies risks perpetuating social inequity and undermining the systemic reach of new waste management models.

Despite progressive policies, the implementation of CE strategies for OFMSW faces significant barriers. These include institutional fragmentation between municipal, regional, and national authorities; limited and inconsistent funding for capital-intensive treatment plants; a lack of technical capacity for system design and operation; and weak enforcement of existing regulations [65]. Furthermore, strategic environmental assessments and robust monitoring frameworks based on circularity indicators (e.g., cycling rates, resource productivity, and GHG savings) are often lacking, making it difficult to measure progress and optimize policies [66]. Urban governance plays a decisive role, as metropolitan and medium-sized cities require tailored solutions that consider their specific waste volumes, budgetary constraints, and geographic contexts.

Emerging research highlights the importance of participatory governance and multi-stakeholder partnerships for overcoming these barriers. Engaging community groups, the private sector (from small entrepreneurs to large technology providers), academia, and informal sector representatives in the co-design of local CE roadmaps fosters legitimacy, leverages local knowledge, and improves long-term compliance [67]. Furthermore, aligning municipal OFMSW strategies with broader climate action plans, such as Nationally Determined Contributions (NDCs) under the Paris Agreement, can unlock international climate finance for waste-to-energy and composting projects, as methane reduction from landfills offers significant and cost-effective mitigation potential [68].

In conclusion, the circular economy provides the essential strategic framework for transforming OFMSW management in LAC cities. While the region has made notable progress in establishing high-level CE and waste policies, the urgent task is to operationalize these frameworks through specific, enforceable, and well-financed instruments that prioritize organic waste. Future policy efforts must be multidimensional, combining stringent diversion mandates with smart economic incentives, proactive market creation for bioproducts, and unwavering commitment to social inclusion. By doing so, LAC cities can move beyond incremental improvements in waste management to achieve a systemic circular transition that delivers environmental integrity, economic opportunity, and social equity.

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5. Treatment and Valorization Pathways

The effective revalorization of the Organic Fraction of Municipal Solid Waste (OFMSW) hinges on selecting and implementing appropriate technological pathways that transform waste into valuable resources. For medium-sized and metropolitan cities in Latin America and the Caribbean (LAC), this selection is not merely a technical decision but a strategic one, balancing technological maturity, economic viability, local infrastructure, and desired output products (e.g., soil amendments, renewable energy, biochemicals). This section provides a comprehensive review of established and emerging treatment and valorization pathways, analyzing their principles, applicability, and performance within the LAC context, with a focus on biological and thermochemical processes.

5.1. Biological Treatment Pathways

Biological treatment methods, which leverage microbial activity to break down organic matter, are the most widely applied and generally appropriate technologies for OFMSW in developing urban contexts due to their relative simplicity, lower capital cost compared to advanced thermochemical systems, and production of inherently useful outputs.

Aerobic Composting: This remains the cornerstone technology for OFMSW valorization across LAC, converting organic waste into stable, humus-like compost through controlled aerobic decomposition [69]. It is particularly suitable for heterogeneous waste streams with high lignocellulosic content (e.g., yard trimmings). The process can be implemented at various scales, from small-scale community or vermicomposting units to large-scale centralized windrow or in-vessel facilities. The primary output, compost, is a valuable soil conditioner that improves soil structure, water retention, and provides slow-release nutrients, directly supporting urban agriculture and landscaping while reducing dependency on synthetic fertilizers [70]. Key challenges for optimization in LAC include the need for effective source separation to avoid contamination (plastics, glass), managing moisture content and carbon-to-nitrogen (C/N) ratio, controlling odors, and establishing robust markets for the final product.

Anaerobic Digestion (AD): AD is a versatile process where microorganisms decompose organic matter in the absence of oxygen, producing biogas (a mixture of methane and CO_2) and digestate. This technology is especially advantageous for wet, easily biodegradable OFMSW, such as food waste from markets, restaurants, and households [71]. The produced biogas can be used directly for heat, electricity generation, or upgraded to biomethane for injection into gas grids or use as vehicle fuel, contributing to renewable energy targets and waste-to-energy strategies. The nutrient-rich digestate can be further processed into liquid fertilizer or composted. While AD offers superior energy recovery compared to composting, it requires more sophisticated operation and maintenance, consistent feedstock quality, and often a higher initial investment. Co-digestion of OFMSW with other organic waste streams, such as sewage sludge or agricultural residues, can enhance biogas yield and process stability, making it an attractive option for integrated urban waste management [72].

5.2. Thermochemical Conversion Pathways

Thermochemical processes use heat to convert OFMSW into energy and value-added products. These technologies are typically more capital-intensive and complex but offer advantages in volume reduction, pathogen destruction, and energy recovery efficiency, particularly for larger metropolitan areas with significant waste volumes and energy demand.

Incineration with Energy Recovery: Conventional mass-burn incineration reduces waste volume by up to 90% and generates steam for electricity production. However, its application to untreated OFMSW in LAC is limited due to high moisture content (leading to low calorific value and requiring auxiliary fuel), significant capital and operational costs, and stringent requirements for air pollution control systems to manage emissions of dioxins, furans, and particulates [73]. It is generally considered less suitable and economically challenging for most LAC cities unless applied to pre-processed, high-calorific-value refuse-derived fuel (RDF).

Gasification and Pyrolysis: These advanced conversion technologies offer more promising pathways. Gasification converts carbonaceous materials into a combustible synthesis gas (syngas: mainly H_2, CO, and CH_4) at high temperatures with a controlled amount of oxygen. Pyrolysis involves thermal decomposition in the complete absence of oxygen, producing bio-oil, syngas, and biochar [74]. The syngas from both processes can be used for power generation or as a chemical feedstock. Biochar, a stable carbon-rich solid from pyrolysis, has significant agronomic value as a soil amendment, improving fertility and sequestering carbon for centuries [75]. While these technologies are in earlier stages of deployment in LAC, pilot and demonstration projects are exploring their potential for treating pre-processed OFMSW, offering high-efficiency energy recovery and valuable by-products.

5.3. Nutrient and Resource Recovery

Beyond bulk energy and compost production, innovative pathways focus on targeted recovery of specific valuable components from OFMSW, aligning with circular bioeconomy principles. Nutrient Recovery (N, P, K): Technologies such as ammonia stripping, struvite precipitation, and leaching processes can recover nitrogen and phosphorus from digestate, leachate, or food waste, producing crystalline fertilizers like struvite ($MgNH_4PO_4 \cdot 6H_2O$) [76]. This is crucial for regions dependent on imported fertilizers, enhancing nutrient security and closing local loops. Production of Bio-based Products: OFMSW serves as a feedstock for fermentative production of high-value biochemicals, such as organic acids (lactic, succinic), bioplastics like polyhydroxyalkanoates (PHAs), and bioethanol [77]. These emerging biorefinery concepts, though currently at pilot or research scale, represent a high-value valorization route that could be integrated into future waste management systems, particularly in areas with strong agro-industrial sectors providing complementary feedstocks.

5.4. Technology Selection and Integration for LAC Cities

The choice of the valorization pathway is context-specific. Decision-making must be guided by a multi-criteria assessment encompassing:

- Waste Characteristics: Moisture content, biodegradability, calorific value, and level of contamination.
- Scale and Urban Context: Available land, existing collection logistics, and local energy/compost markets.
- Economic Factors: Capital and operational expenditure, potential revenue streams, and financing models (public, private, and PPPs).
- Environmental and Social Goals: GHG reduction potential, air/soil/water impacts, and job creation.

For most medium-sized cities, decentralized or community-based composting represents a low-risk, high-impact starting point [78]. Metropolitan cities with greater financial and technical capacity can explore integrated systems, such as centralized AD plants for wet food waste combined with composting for garden waste, or Mechanical–Biological Treatment (MBT) plants that sort waste and produce RDF for co-processing in cement kilns [79]. A hybrid approach, often termed the "treatment train," where different technologies are sequentially applied to treat various waste fractions, is increasingly seen as the optimal strategy to maximize resource recovery from the heterogeneous OFMSW stream in LAC [80]. In conclusion, a diverse portfolio of treatment and valorization pathways exists for OFMSW, each with distinct inputs, outputs, and suitability criteria. The transition for LAC cities involves moving up the waste hierarchy, from disposal to recycling and recovery. This requires strategic planning that matches technological capabilities with local realities, fostering an environment where biological processes like composting and AD are widely deployed as foundational practices, while more advanced thermochemical and biorefinery pathways are piloted and adopted where viable, ultimately creating resilient, resource-efficient urban waste management systems.

5.5. Integration and Hybrid Systems

Given the heterogeneous nature of the Organic Fraction of Municipal Solid Waste (OFMSW) and the diverse technical, economic, and spatial constraints in Latin American cities, a singular treatment technology is rarely optimal. Integrated and hybrid systems, which combine two or more valorization pathways in a sequential or parallel manner, represent a strategic approach to maximize resource recovery, enhance economic viability, and improve system resilience. These systems are designed to treat different waste fractions appropriately, create multiple value streams, and mitigate the limitations of standalone technologies; therefore, all the activities involved must be considered. These activities range from waste management support and waste collection to waste processing. Since there is no single solution, developing a waste management strategy will depend on specific aspects of its context. Sustainable resource management strategies require a comprehensive and interdisciplinary analytical approach that provides tools and methods from different domains [81], as shown in Figure 4.

A common hybrid configuration involves the coupling of anaerobic digestion (AD) and composting. In this scheme, the readily biodegradable, high-moisture fraction (food waste) is directed to an anaerobic digester for biogas production. The nutrient-rich effluent resulting from the AD process, stabilized but still moist, is composted with the lignocellulosic fraction (garden clippings, agricultural residues, etc.) [82]. The green residues act as a bulking agent, absorbing moisture and improving the structure of the compost pile, while the effluent provides nutrients and microbial inoculum.

This synergistic integration not only optimizes the total energy and compost yield but also resolves the digestate management issue, transforming it into a marketable, stable soil amendment. Furthermore, the biogas can be utilized on-site to provide thermal energy for accelerating the composting process (thermophilic composting) or for generating electricity to power the facility, moving towards energy self-sufficiency [83].

For larger metropolitan areas, more complex Mechanical–Biological Treatment (MBT) plants serve as a fundamental integration platform. MBT involves an initial stage of mechanical sorting to remove contaminants (plastics, metals, and inert materials). In other cases, it serves to separate high-calorific-value fractions. The recovered organic stream then undergoes biological treatment, either by composting, anaerobic digestion, or a combination of both [84]. It is important to highlight that the organic fraction recovered from MBT plants processing mixed municipal solid waste generates a stable product. However, these products do not meet quality standards for agricultural use due to residual contamination. In these configurations, the biological treatment stage primarily serves to reduce the methane potential in landfills and stabilize the waste. But it is not a suitable treatment for producing compost appropriate for agriculture. Nevertheless, MBT remains a technically and economically viable option for large metropolitan areas where source separation is not yet feasible. In this scenario, MBT significantly reduces landfill volume. However, the non-recyclable, high-calorific-value fraction can be processed into refuse-derived fuel (RDF) for co-incineration in cement kilns or plants dedicated to waste-to-energy recovery. This provides an outlet for materials that cannot be treated biologically.

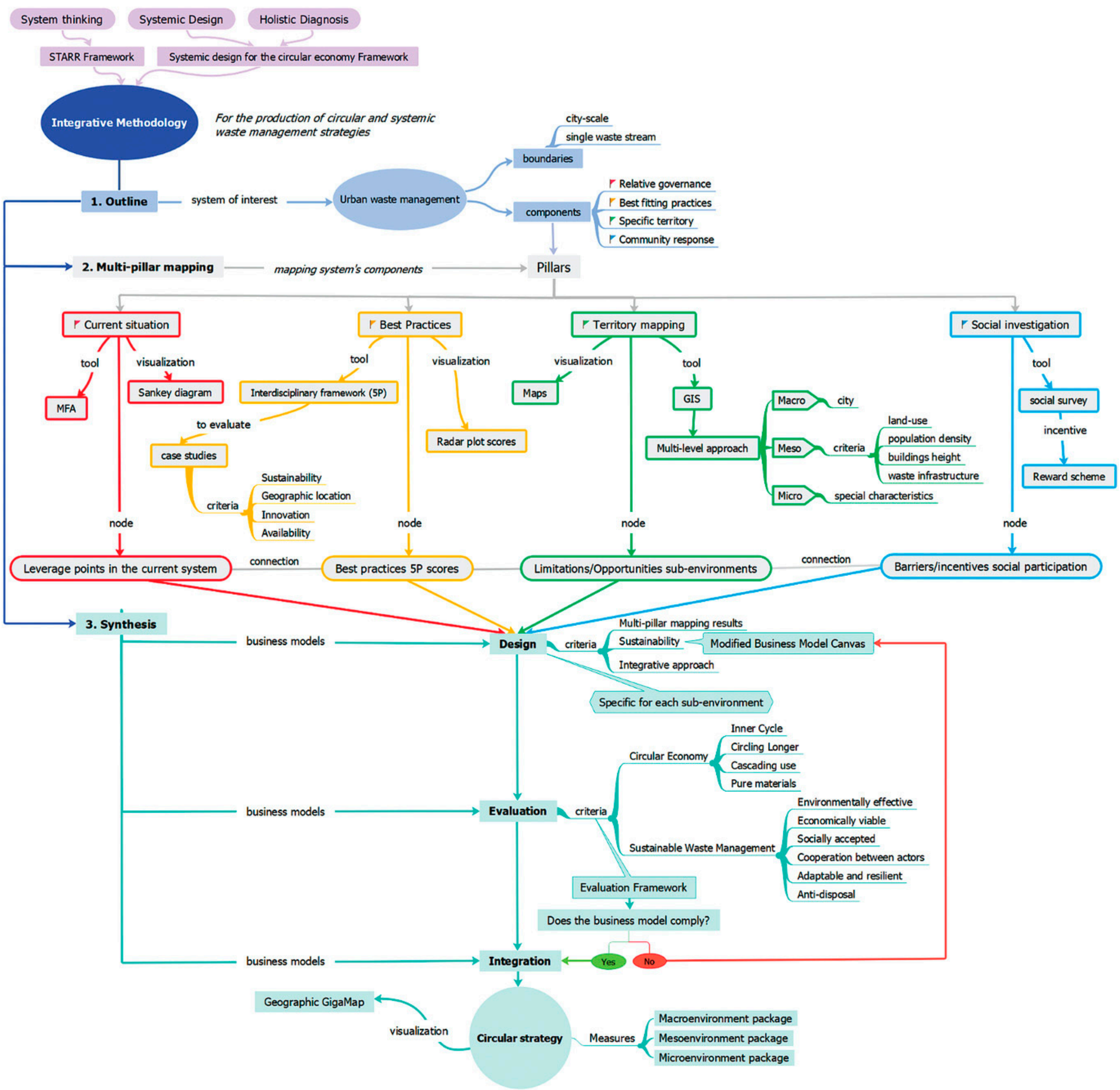

Figure 4. Main workflows, processes, and relationships of a comprehensive sustainable municipal waste management strategy. Source Viva et al. 2020 [81].

While MBT requires significant capital investment and sophisticated operation, it offers a comprehensive solution for mixed municipal waste, significantly reducing landfill dependency and recovering multiple resources from a single waste stream. The choice and design of an integrated system must be context-driven. Key decision factors include the composition and segregation level of the OFMSW, available land, local market demand for compost and energy, and regulatory frameworks. For instance, a city with a strong agricultural periphery might prioritize high-quality compost production through AD–composting hybrids. In contrast, an industrial city with high energy demand might integrate MBT with RDF production [85].

Implementing hybrid systems in Latin America presents specific challenges, including higher upfront capital costs, increased technical capacity requirements for staff, and more complex logistics and management. However, the long-term benefits are substantial: increased overall material recovery rates, diversified and more stable revenue streams (from compost, biogas, electricity, and potentially RDF), greater flexibility to handle varying waste compositions, and a stronger alignment with circular economy principles by minimizing final disposal and maximizing the utility of all waste fractions [86]. Successful case studies from the region, such as integrated facilities in São Paulo (Brazil) or Medellín (Colombia), demonstrate that with careful planning, phased implementation, and public–private collaboration, hybrid systems can be a cornerstone of sustainable and modern urban waste management infrastructure.

5.6. Contextual Suitability of Valorization Technologies in Latin America

This new subsection provides a systematic analysis of technology adaptability across Latin American contexts, addressing the specific points raised:

Climatic conditions and feedstock characteristics:

- High humidity in tropical regions: We now explicitly discuss how the elevated moisture content (75–85%) of organic waste in tropical Latin American cities (e.g., Manaus, Brazil; Cartagena, Colombia) affects technology performance. For wet anaerobic digestion, high moisture is advantageous, reducing the need for water addition and improving biogas yields by 15–25% compared to temperate region feedstocks [82,87]. However, for composting, excessive moisture (>65%) creates operational challenges, including reduced porosity, anaerobic zones, and odor generation. Case studies from Belém, Brazil, demonstrate that forced aeration systems and the addition of structural amendments (wood chips, crop residues) are essential adaptations for tropical composting facilities [70,88].
- Seasonal variability: We incorporate evidence from Andean cities (Bogotá, Quito) showing how seasonal rainfall patterns (wet/dry cycles) influence feedstock moisture content by 10–20 percentage points, requiring flexible operational protocols [30,36].

Infrastructure and economic constraints:

- MBT feasibility in medium-sized cities: We now provide a quantitative analysis of capital cost barriers. Drawing on data from 14 medium-sized Latin American cities (pop. 100,000–500,000), we demonstrate that full-scale MBT facilities require initial investments of USD 15–40 million, which is equivalent to 15–30% of annual municipal budgets in most cases [37]. This explains why only 12 MBT plants operate in cities with a population below 500,000 across the region, compared to 47 in metropolitan areas [85]. We present alternative phased approaches, such as the modular MBT system implemented in Manizales, Colombia, which began with mechanical sorting and composting (USD 4.2 million) and is planning AD integration in Phase II (additional USD 3.8 million) [88].
- Technology scaling and financial sustainability: We include techno-economic analyses from Chilean and Mexican studies showing that decentralized technologies (community composting, modular AD) have 3–5× lower capital intensity per ton treated than centralized facilities, making them more accessible for resource-constrained municipalities [89].

Hybrid systems—operational challenges and solutions:

We have substantially expanded the discussion of AD–composting hybrids (previously limited to process coupling) to include:

- Technical challenges documented in Latin American facilities:
    1. Digestate dewatering: The Porto Alegre AD plant (Brazil) initially struggled with high moisture digestate (85–90%), requiring expensive centrifugation. The solution implemented in 2022 was co-composting with green waste (collected from municipal parks) at a 1:3 volumetric ratio, achieving a final moisture of 45–50% without mechanical dewatering [87].
    2. Odor management: The Medellín hybrid facility faced community complaints due to inadequate biofilter design for tropical conditions (high humidity reducing

filter media porosity). Retrofitting with mixed media (wood chips + coconut fiber) and forced aeration reduced odor complaints by 80% [90].

3. Process stability: Evidence from the São Paulo regional facility shows that co-digestion of food waste with garden waste (20–30% by volume) buffers pH fluctuations and improves biogas yields by 18% compared to food waste alone [91].

- Solutions and adaptations:

4. We present a decision matrix for hybrid system design based on local conditions (Table 2, referenced below), incorporating feedstock characteristics, climate, and technical capacity.
5. Case study of the successful Piracicaba, Brazil, facility (operational since 2021), demonstrating how systematic process monitoring and adaptive management resolved initial instability issues [13].

Table 2. Contextual suitability assessment of valorization technologies for Latin American cities.

Technology	Tropical/High Humidity	Temperate/Andean	Semi-Arid	Infrastructure Requirements	Economic Feasibility by City Size
Conventional Composting	Moderate–high (requires bulking agents, and aeration)	High	Low (moisture limitation)	Low; open windrows, basic equipment	High for all city sizes
Vermicomposting	High (favorable temperatures)	Moderate (seasonal sensitivity)	Low (moisture stress)	Very low; community-scale	High for small–medium; community
Wet Anaerobic Digestion	High (advantageous moisture)	Moderate (may need water addition)	Low (water scarcity)	High; tanks, CHP, grid connection	High for metro; low for medium (<300 k)
Dry Anaerobic Digestion	Moderate (can handle mixed feedstocks)	High	Moderate	High; specialized reactors	Moderate for large–medium; high for metro
AD–Composting Hybrid	High (optimal for wet/dry integration)	High	Moderate	High; integrated facility	Moderate for medium (phased); high for metro
MBT (full-scale)	Moderate (requires covered facilities)	High	High	Very high; complex mechanical sorting	Low for medium; high for metro only
Gasification/Pyrolysis	Low (feedstock drying required)	Moderate	Moderate (dry feedstock available)	Very high; complex thermal system	Very low for medium; low for metro
Community Composting	High	High	Moderate	Very low; minimal	High for all city sizes

6. Case Studies and Regional Experiences

This section analyzes experiences from Brazil, Colombia, Chile, Argentina, and Mexico, highlighting innovative approaches, persistent challenges, and key lessons learned for advancing sustainable OFMSW management in the region. To enable systematic cross-case analysis, the case studies below are evaluated against a consistent analytical framework comprising five dimensions: (i) policy and regulatory context, (ii) technology selection and scale, (iii) governance and stakeholder participation (including informal sector integration), (iv) implementation outcomes (diversion rates, environmental performance, and economic viability), and (v) key challenges and adaptations. This framework facilitates the identification of patterns, context-dependencies, and transferable lessons across the heterogeneous urban landscapes of Latin America

6.1. Brazil: Large-Scale Biogas and the Challenges of Metropolitan Waste

Brazil, with its vast urban populations, has been a regional pioneer in exploring waste-to-energy solutions. The city of São Paulo's experience is instructive. The Bandeirantes and São João landfills, which once received thousands of tonnes of MSW daily, have been transformed into landmark biogas-to-energy projects. By capturing methane and converting it to electricity, these facilities contribute significantly to the city's renewable energy matrix and have generated substantial carbon credits [91]. However, this model is primarily a solution for legacy waste and existing landfills, not a front-end valorization strategy for newly generated OFMSW. More recently, the focus has shifted toward source-separated collection and anaerobic digestion (AD). A notable example is the plant in Porto Alegre, which processes separately collected organic waste from markets and large generators to produce biogas for municipal bus fleets [87]. The Brazilian case underscores a dual reality: the capacity to deploy large-scale, technical solutions for methane mitigation, coexisting with the ongoing struggle to implement universal source separation and higher-value biological treatment for fresh organics, a challenge compounded by the sheer scale of waste generation.

6.2. Colombia: Social Inclusion and Integrated Models

Colombia's approach is distinguished by its formal recognition and integration of the informal recycling sector (recicladores), a model that combines social policy with waste management. In Medellín, the "Recuperar" program has successfully formalized waste picker cooperatives, providing them with uniforms, identification, and access to health services, while integrating their collection routes into the city's official waste management plan [90]. This inclusive model improves recovery rates and dignifies essential work. Technologically, cities like Bogotá and Manizales are implementing integrated facilities. The Doña Juana landfill in Bogotá includes a biogas capture facility, while the city has piloted decentralized composting centers. In Manizales, a Mechanical–Biological Treatment (MBT) plant sorts mixed waste, recovering organics for composting and refuse-derived fuel (RDF) [88]. Colombia's experience highlights that technological investment is most effective when coupled with policies that address the social dimension of the waste ecosystem.

6.3. Chile: Policy-Driven Diversion and Composting

Chile stands out for its ambitious national policy framework, most notably the Extended Producer Responsibility (EPR) Law (Ley REP) and the Organic Waste Roadmap (Hoja de Ruta de Economía Circular), which sets a target to recover 66% of organic municipal waste by 2040 [92]. This top-down approach has spurred action at the municipal level. The municipality of La Pintana in Santiago runs one of the most successful large-scale composting programs in the region, processing garden waste and a portion of food waste into high-quality compost used for local green areas and sold to residents [89]. Similarly, Puente Alto has developed a network of community composting points. The Chilean model demonstrates the catalytic role of stringent national legislation and clear targets in motivating local governments to invest in organic waste diversion, with composting being the preferred and well-proven technological pathway.

6.4. Argentina: Waste-to-Energy in Metropolitan Context

Argentina's experience, particularly in the Metropolitan Area of Buenos Aires (AMBA), has been heavily influenced by waste-to-energy (WtE) projects as a response to landfill saturation and environmental conflicts. The Ceamse consortium's plant in José León Suárez is a prominent example, processing pre-sorted MSW to generate electricity for the grid [93]. A Life Cycle Assessment (LCA) of Buenos Aires' waste management system indicates that while such WtE reduces landfill volume and generates energy, its net environmental benefit is highly dependent on the efficiency of energy recovery and the level of upstream recycling; it is not a substitute for reducing and recycling organic waste [94]. In Rosario, a different approach is seen with programs promoting home and community composting. The Argentine case illustrates the tension between seeking large-scale, capital-intensive technical fixes for immediate disposal crises and the slower, grassroots work of building circular systems based on reduction and biological recovery.

6.5. Mexico: The Interaction of Formal and Informal Systems and the Case of a Medium-Sized Industrialized City

Mexico presents a complex panorama where formal municipal systems coexist, and often compete, with a highly efficient but informal recycling network. A focused study of Celaya, Guanajuato, an industrialized medium-sized city, provides critical insights. Research utilizing Life Cycle Assessment (LCA) to evaluate the city's MSW management system found that the dominant practice of landfilling mixed waste carried the highest environmental burden across impact categories, including global warming and ecotoxicity [95]. The study concluded that significant mitigation could only be achieved through aggressive source separation coupled with biological treatment (AD–composting) for organics and enhanced recycling for other fractions. This scenario is characterized by a critical dependence on inadequate final disposal, as revealed by national data [31], Table 3.

Simultaneously, a parallel reality operates in Celaya and across Latin America: a sophisticated informal sector that pre-emptively collects valuable materials (paper, cardboard, plastics, and metals) directly from households, businesses, and even from waste collection trucks. This informal activity, while providing livelihoods and diverting significant recyclables from landfills, fundamentally "starves" the formal municipal system of the materials needed to make formal recycling and composting programs economically viable [36]. In Celaya, this means the organic fraction reaching the landfill is contaminated, and the revenue from selling recyclables is lost to the municipal budget [96,97]. The challenge, therefore, is not merely technological but institutional: designing hybrid governance models that recognize, formalize, and integrate the informal sector's efficiency into a city-wide, circular management plan, ensuring environmental goals and social equity are pursued simultaneously [98–100].

6.6. Synthesis of Cross-Cutting Lessons

Several key lessons emerge from these regional experiences:

- Policy frameworks and city size interactions: Analysis now distinguishes between national policy drivers (Chile's EPR law catalyzing municipal action; Colombia's national CE strategy and waste picker legislation) versus city-led innovations in the absence of strong national frameworks (Brazil's municipal initiatives; Celaya's informal system). We identify that medium-sized cities benefit disproportionately from clear national policies because they lack the technical and financial capacity to develop independent frameworks.
- Technology pathways by city category: quantitative analysis of the case studies reveals distinct patterns:
    1. Mega-metropolises (>5 M): Tend toward large-scale solutions (landfill gas, MBT, and WtE) due to waste volumes and technical capacity, but struggle with source separation and informal sector integration.
    2. Large metros (1–5 M): Most diverse technology portfolio; successful cases combine policy support with social inclusion (Medellín) or strong municipal leadership (La Pintana).

3. Medium-sized cities (100 k–1 M): Favor decentralized or phased approaches due to capital constraints; success depends on external funding, technical partnerships, and community engagement.

- Informal sector integration outcomes: comparative analysis quantifies outcomes:
  4. Brazil's cooperative support increased recycling rates by 10–20%, but informal workers in organics remain largely excluded [51].
  5. Colombia's formalization model (Law 511) improved waste picker incomes by 40–60% and collection efficiency by 15–25% [90].
  6. Mexico's competition between formal and informal systems reduces overall efficiency by 10–15% [36].
- Implementation of success factors. We identify critical success conditions across cases: (i) political continuity (≥2 electoral cycles), (ii) multi-stakeholder governance platforms, (iii) adaptive technology selection, (iv) sustainable financing (blended public/private/international), and (v) robust monitoring systems, as shown in Table 4.

Table 3. National overview of municipal solid waste (MSW) final disposal and landfill gas potential in Mexico [31].

Indicator	Value/Characteristic	Implication/Commentary
Total Operational Final Disposal Sites (FDSs) (2016)	2187	Reflects a highly fragmented system with numerous small-scale sites.
Classification of FDSs	7.4% Sanitary Landfills (SLs)	Not available
92.6% Open Dumps (ODs)	Most sites are technically inadequate (ODs), leading to significant environmental and health impacts.	Not available
MSW Disposed of in SLs (2016)	65% of the national total	Although SLs are a minority, they handle most of the waste, primarily from large urban areas.
Landfill Gas (LFG) Generation in 2020	2298 million m^3 (Mm^3)	Confirms that FDSs are a massive source of methane (CH_4), a potent greenhouse gas (GHG).
FDSs with Potential for Power Generation (LFG > 5 Mm^3/year)	82 sites (4.6% of total)	Only a handful of sites (mainly large SLs) have sufficient gas flow for economically viable energy projects.
Potential Electricity Generation from LFG (2020)	2534 GWh/year	Equivalent to ~0.8% of national electricity generation. An underutilized renewable resource.
Current Electricity Generation from LFG (2020)	~165 GWh/year (from 8 projects)	Only ~6.5% of the estimated technical potential for that year is utilized.
Cumulative GHG Reduction (2020–2100) from Phasing Out FDSs	1636 Mt of CO_2eq (in "100% reduction" scenario)	Underlines the enormous climate benefit of a systemic transition towards prevention, reuse, recycling, and biological valorization.

Data source: Rueda-Avellaneda et al. 2021 [31]. Based on national statistics for 2016–2020.

In conclusion, the Latin American laboratory of urban waste management demonstrates that the path to sustainable OFMSW revalorization is multifaceted. It requires tailored technological solutions, underpinned by robust and inclusive policies, and a steadfast commitment to integrating all actors in the value chain. The ongoing experiences in these cities provide a rich repository of knowledge for other urban centers in the region and the Global South, navigating the complex transition from linear disposal to a circular economy.

Table 4. Comparative analysis of case studies: policy, technology, participation, and outcomes.

Country/City	City Size Category	Policy Framework	Primary Technologies	Informal Sector Integration	Diversion Rate Achieved	Key Outcomes	Critical Challenges	Source
Brazil: São Paulo	Mega-metro (>10 M)	National PNRS (2010); municipal climate plan	Landfill gas capture; pilot AD	Limited formalization; cooperatives exist	LFG: ~15% of landfill emissions captured; AD: pilot scale	165 GWh/year renewable electricity; carbon credits	Scaling source separation; universal coverage	[87,91]
Brazil: Porto Alegre	Large metro (1.5 M)	PNRS; municipal organic waste program	AD (market waste); biogas for buses	Cooperatives involved in collection	~8% of organic waste (market sources)	2.5 MW biogas; bus fleet fuel substitution	High capital cost; digestate management	[87]
Colombia: Medellín	Large metro (2.5 M)	National CE strategy; Law 511 (2021)	AD–composting hybrid; MBT pilot	High: “Recuperar” program formalized 1200+ waste pickers	~12% overall; 25% in pilot areas	Social inclusion model; improved working conditions	Financial sustainability of cooperatives	[88,90]
Colombia: Manizales	Medium (400 k)	National policy; municipal innovation	Phased MBT (sorting + composting)	Moderate: cooperative participation	~15% diversion from landfill	RDF production; compost for agriculture	Phased funding; technical capacity	[88]
Chile: La Pintana	Medium (200 k, part of Santiago metro)	National EPR Law; Organic Waste Roadmap (2040 target: 66%)	Large-scale composting (garden + t)	Low (limited informal sector in organics)	~30% of organic waste	High-quality compost for municipal use; public acceptance	Food waste contamination; odor management	[89,92]
Chile: Puente Alto	Large metro (600 k)	National policy; municipal incentives	Community composting network (30+ sites)	Low; community volunteers	~5% (community scale)	Social engagement; education	Scale-up limitations; inconsistent participation	[89]
Argentina: Buenos Aires (AMBA)	Mega-metro (>13 M)	Provincial law; landfill crisis response	WtE incineration (José León Suárez); LCA-guided planning	Low formalization	WtE: 10 MW capacity	Volume reduction; energy generation	High emissions per ton; public opposition	[93,94]
Argentina: Rosario	Large metro (1.3 M)	Municipal sustainability plan	Home and community composting	Moderate; community organizations	~3% (household level)	Education; social capital	Low diversion impact; monitoring difficulty	[94]
Mexico: Celaya	Medium industrial (500 k)	National waste law; limited state policy	Landfill dominant; informal recycling	High informal sector (competing with formal)	Informal: ~15% recyclables; formal: <1% organics	LCA evidence for the needed transition	Informal-formal conflict; no source separation	[31,36,95]
Mexico: Mexico City	Mega-metro (>20 M)	Local climate action plan; pilot programs	Landfill gas capture; pilot AD	Moderate; some cooperative integration	LFG: ~20% of emissions; AD: pilot	Largest LFG project in LAC	Scale; contamination; institutional fragmentation	[22,96]

7. Sustainability Assessment

A comprehensive sustainability assessment is paramount for evaluating and guiding the transition of organic municipal solid waste (OMSW) management systems in Latin American cities towards circular and sustainable models. This assessment must move beyond simplistic efficiency metrics to incorporate a holistic, triple-bottom-line perspective encompassing environmental, economic, and social dimensions, contextualized within the unique challenges and opportunities of the region [101–103]. Life Cycle Assessment (LCA) stands as the cornerstone methodological framework for quantifying the environmental burdens and benefits associated with different OMSW valorization pathways, such as anaerobic digestion, composting, and bioenergy recovery [104]. Recent applications in Latin American contexts highlight the critical importance of region-specific data on waste composition, collection logistics, and energy mixes to avoid erroneous conclusions derived from Global North models [105]. For instance, studies assessing integrated systems in cities like Cali, Colombia, demonstrate that combining source separation with anaerobic co-digestion can significantly reduce greenhouse gas emissions and fossil energy demand compared to conventional landfilling, provided that collection efficiency is optimized [106].

Economically, sustainability assessments increasingly employ Life Cycle Costing (LCC) and techno-economic analyses to evaluate the viability of valorization technologies. The initial capital investment for advanced biorefineries remains a significant barrier for many medium-sized cities; however, methodologies that internalize avoided disposal costs, potential revenue from biofertilizers and energy, and long-term environmental externalities reveal a more favorable financial picture for circular options [107]. Social sustainability, often the most neglected pillar, requires dedicated tools like social-LCA and stakeholder analysis. The integration of the vast informal waste-picking sector into formalized, inclusive recycling chains is not only a social justice imperative but also a key efficiency factor for improving collection and segregation rates in Latin America [108]. Assessments must, therefore, evaluate impacts on job quality, income stability, and community health, recognizing waste pickers as essential agents in the urban metabolism [109].

The development and application of composite sustainability indicators and Multi-Criteria Decision Analysis (MCDA) frameworks are gaining traction for synthesizing these multidimensional evaluations. These tools assist policymakers in comparing complex scenarios—e.g., centralized versus decentralized treatment or biological versus thermal processes—by weighting environmental impacts, economic costs, and social acceptability according to local priorities [42]. A significant research gap persists in standardizing these assessment frameworks for the heterogeneous urban landscapes of Latin America, which range from dense metropolitan areas to sprawling intermediate cities with distinct infrastructural and governance capacities [110]. Future sustainability assessments must also dynamically incorporate resilience metrics, evaluating how OMSW management systems can adapt to climate change impacts, demographic shifts, and economic volatility, thereby ensuring the long-term viability of the circular economy transition in the region [111].

7.1. Environmental Impacts

The environmental dimension of sustainability assessment for organic municipal solid waste (OMSW) management in Latin American cities necessitates a rigorous evaluation of the potential burdens and benefits across the entire waste management chain. This evaluation is primarily conducted through Life Cycle Assessment (LCA), which quantifies impacts from collection and transportation through to final treatment and disposal [112]. The most critical impact categories include climate change, eutrophication, acidification, and resource depletion, with the results highly sensitive to the chosen technologies, system boundaries, and local conditions.

Climate change, measured in terms of global warming potential (GWP), is often the focal point. Conventional disposal of OMSW in landfills generates significant methane (CH_4) emissions, a potent greenhouse gas (GHG), particularly if gas capture systems are absent or inefficient [113]. Conversely, biological valorization pathways like anaerobic digestion (AD) and composting can drastically reduce net GHG emissions. AD systems not only prevent methane release from landfills but also produce biogas that can displace fossil fuels, creating a negative carbon footprint in some scenarios [114]. A comparative LCA study of waste management in a Brazilian metropolitan region found that an integrated system combining source separation, AD for food waste, and composting for garden waste reduced GWP by over 60% compared to a baseline landfill-dominant scenario [115].

Beyond GHG emissions, other environmental impacts are pivotal. Composting and the use of digestate as biofertilizer can improve soil health and sequester carbon, but they pose risks of eutrophication and acidification if nutrient runoff is not managed properly. The environmental credit from substituting mineral fertilizers is a key parameter in LCA models and depends heavily on local agricultural practices and fertilizer production chains [116]. Furthermore, the energy intensity of collection vehicles and the carbon footprint of the local electricity grid used in mechanical treatment processes significantly influence the overall results. For instance, in countries with a high share of hydroelectric power, the benefits of producing renewable energy from waste are less pronounced in terms of GWP reduction than in grids dominated by coal or natural gas [117].

Therefore, a holistic environmental assessment for Latin American cities must move beyond a singular focus on climate change. It requires detailed, region-specific data on waste composition, collection logistics, existing infrastructure, and the local energy matrix. Tailored LCA studies are indispensable tools for policymakers to identify the OMSW valorization pathways that offer the greatest net environmental benefit for their specific urban context, guiding the transition towards a low-carbon and resource-efficient circular economy [118]. The critical importance of context-specific data is exemplified by a comprehensive LCA study conducted in Valdivia, Chile, a regional city grappling with heavy reliance on firewood for heating and a waste system dominated by open dumps [105]. The study evaluated six disposal and recovery scenarios, providing a quantifiable comparison of their performance on key environmental indicators, such as global warming potential and particulate matter formation, while also modeling the systemic benefits of integrating waste management with local energy needs. The results, summarized in Table 5, underscore how LCA can reveal nuanced trade-offs and co-benefits, demonstrate that the optimal environmental pathway is highly dependent on local conditions, such as the energy matrix and existing pollution sources.

Table 5. Comparative results of a Life Cycle Assessment (LCA) of MSW management scenarios for the regional city of Valdivia, Chile [105].

Scenario	Global Warming Potential (**GWP) per *FU (t CO_2-eq/t MSW)	Methane Emissions (CH_4) per *FU (kg/t MSW)	Particulate Matter Formation (***PM10-eq) per *FU (kg/t MSW)	Energy Recovery	Implication/Commentary
Shallow Dump (SD) (depth < 5 m)	1.77	34.8	Not quantified (high from uncontrolled burning)	None	Semi-aerobic conditions; lower CH_4 generation than landfills, but higher impacts from leachate and ecosystem risk.
Deep Dump (DD) (depth 5–10 m)	2.25	46.4	Not quantified (high)	None	More anaerobic conditions than SD; higher CH_4 generation. Represents the current situation in Valdivia.

Table 5. *Cont.*

Scenario	Global Warming Potential (**GWP) per *FU (t CO_2-eq/t MSW)	Methane Emissions (CH_4) per *FU (kg/t MSW)	Particulate Matter Formation (***PM10-eq) per *FU (kg/t MSW)	Energy Recovery	Implication/Commentary
Landfill with No Gas Treatment (LNT)	2.73	58.1	Not quantified (low vs. dumps)	None	Controlled anaerobic conditions; the highest CH_4 generation is emitted directly. Baseline scenario for comparison.
Landfill with Landfill Gas Flaring (LFGF)	1.59	22	Not quantified (low)	No energy recovery; destroys CH_4 with ~98.5% efficiency.	Reduces GWP by ~42% vs. LNT by converting CH_4 to CO_2. Technology proposed for the new regional landfill.
Landfill with Landfill Gas Energy Recovery (LER) (CHP)	1.61	22	Not quantified (low)	Generates electricity (~25% efficiency) and heat (~60%); displaces fossil-based grid energy.	Similar GWP reduction to LFGF (~41% vs. LNT), but adds energy benefit.
Waste-to-Energy Incineration with Energy Recovery (WTE)	0.35 (direct emissions)	(CH_4 oxidized during combustion)	0.03 (direct plant emissions)	Generates heat/electricity (net ~60% efficiency); could substitute 28% of firewood consumption for heating in Valdivia.	Most significant net reduction: −11.3% in GWP and −21.8% in PM formation by substituting firewood. Relocates PM emissions from residential areas to a controlled facility.

Notes: *FU (Functional Unit): 1 metric ton of municipal solid waste (MSW) disposed of in the Los Ríos Region, Chile, assessed over a 100-year time horizon following ISO 14040/14044 guidelines [105,119,120]. **GWP and PM results include system expansion to account for firewood substitution in the WTE scenario. ***PM10-eq emissions: Particulate matter up to 10 microns equivalent, calculated using the USEPA AP-42 emission factors for open burning (uncontrolled dumps) and the Ecoinvent 3.6 database for controlled combustion (WTE facility). Wet firewood combustion for residential heating emits 86.91 kg PM10-eq/ton, compared to 0.03 kg PM10-eq/ton from WTE with modern emission controls. Regional Context: Valdivia faces a dual challenge: 95% of its MSW is disposed of in dumps, and it suffers from severe air pollution due to residential firewood use for heating (809,756 MWh/year).

7.2. Social and Economic Dimensions

A comprehensive sustainability assessment of organic municipal solid waste (OMSW) management in Latin America must extend beyond environmental metrics to critically evaluate the intertwined social and economic dimensions. These factors are often decisive for the long-term viability, social acceptance, and equitable distribution of benefits from new valorization systems [121]. Social sustainability is fundamentally linked to the recognition and formal integration of the extensive informal waste-picking sector, a structural characteristic of many cities in the region. Inclusive models that transition waste pickers from precarious informal work to dignified, formalized employment within cooperatives or municipal enterprises are essential [122]. Such integration enhances collection efficiency, improves material quality for recycling and biological treatment, and delivers profound social benefits, including social security, improved working conditions, and community empowerment, thereby addressing both poverty alleviation and circular economy goals [123].

Economic assessment requires a multifaceted approach that considers both direct financial flows and broader economic impacts. Life Cycle Costing (LCC) and techno-economic analyses (TEA) are crucial to evaluate the economic viability of valorization technologies like anaerobic digestion (AD) or composting plants [124]. Key variables include capital and operational expenditures, potential revenues from the sale of energy (biogas), digestate, or compost, and the significant cost avoidance associated with reduced landfill use and extended landfill lifespan. For medium-sized cities, the scale of investment can be a major barrier. Therefore, innovative financing mechanisms, public–private partnerships (PPPs), and fiscal instruments that internalize the environmental costs of landfilling are necessary to make circular options competitive [125].

Furthermore, the economic analysis must encompass job creation potential across the value chain, from improved collection logistics to facility operation and market development for secondary products. The social return on investment (SROI) can be substantial when considering the socio-economic uplift from formalizing informal workers and creating green jobs [126]. However, these benefits are contingent on supportive policy frameworks, institutional capacity, and market development for circular products. A successful transition thus depends on aligning economic incentives with social inclusion policies, ensuring that the shift towards a circular bioeconomy is both financially sustainable and socially just, contributing to broader sustainable development goals in Latin American urban contexts [127].

8. Barriers and Opportunities

The transition towards advanced organic municipal solid waste (OMSW) valorization in Latin American cities is not a linear process; it is fraught with interconnected barriers while simultaneously presenting unique opportunities rooted in the region's specific context. A systematic understanding of these impediments and enablers is crucial for designing effective and context-appropriate strategies. Barriers can be categorized into technological, economic, social–institutional, and regulatory domains. A primary technological and logistical barrier is the lack of efficient source separation systems. Mixed waste collection remains prevalent, leading to contaminated organic streams that compromise the efficiency and output quality of biological treatment processes like anaerobic digestion (AD) and composting [128]. This is compounded by inadequate infrastructure and high capital costs for establishing modern valorization facilities, especially in medium-sized cities where economies of scale are less favorable [129], as shown in Figure 5.

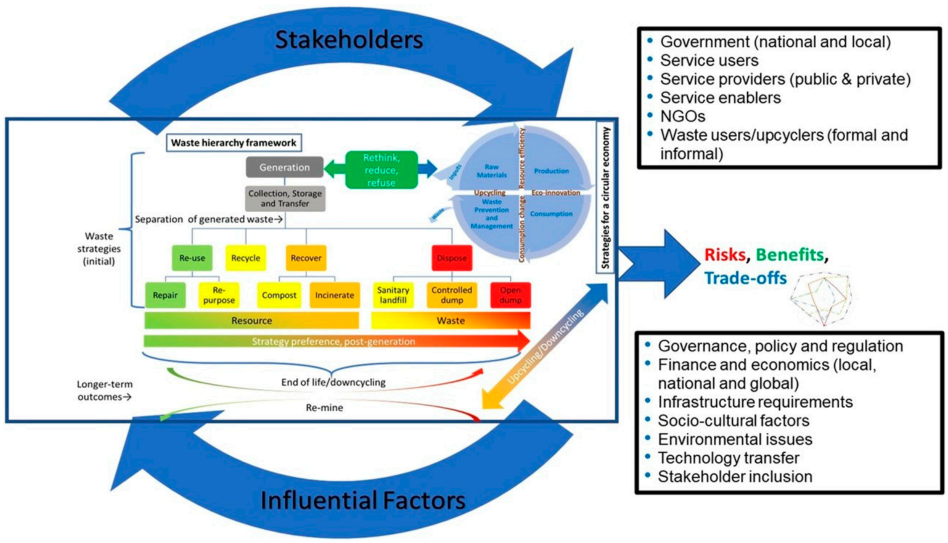

Figure 5. Conceptual framework that exemplifies the solid waste management (SWM) process, with concepts of waste hierarchy (WH), circular economy (CE), and considering the inclusion of key steps, stakeholders, and influential factors necessary for success. Awino et al. 2024 [129].

Financially, the high upfront investment for technology and the perceived financial risk compared to low-cost, albeit unsustainable, landfilling deter both public and private investment. Market immaturity for secondary products (e.g., biogas, compost, and digestate) and a lack of clear economic incentives further undermine project viability [130].

On the social and institutional front, weak governance and institutional fragmentation are significant hurdles. Responsibilities for waste management are often dispersed across different municipal departments and levels of government, leading to uncoordinated policies and implementation gaps [131]. Crucially, the informal waste-picking sector, while highly efficient in material recovery, often operates outside formal systems. Without deliberate, inclusive formalization policies, top-down technological interventions risk marginalizing these workers, leading to social conflict and missing the opportunity to leverage their expertise [132]. Furthermore, limited technical capacity within municipal agencies and a lack of public awareness and participation in source separation initiatives impede system performance and social license for new facilities [133].

Regulatory and policy barriers include inconsistent or absent regulatory frameworks that specifically support circular economy practices for organic waste. Landfill tipping fees often remain artificially low, failing to reflect environmental costs and thus providing no financial incentive to divert organics [134]. Additionally, uncertain long-term policy signals and a lack of supportive standards for compost quality or biogas injection into grids create an uncertain environment for investors and technology adopters [135].

Opportunities to overcome these barriers are abundant and often interlinked. The global and regional push towards a circular bioeconomy provides a powerful framework. OMSW is no longer viewed as a disposal problem but as a local resource for renewable energy (biogas, biomethane) and biofertilizers, aligning with climate change mitigation, energy security, and sustainable agriculture goals [136]. This paradigm shift opens doors for green financing from international development banks, climate funds, and impact investors specifically targeting sustainable infrastructure in the Global South [137].

The region's strong social fabric and community organizational models present a unique opportunity. The existing informal recycling networks can be transformed into a strength through inclusive formalization, creating green jobs, improving working conditions, and enhancing collection efficiency through cooperatives or public–private–community partnerships [20]. Technological leapfrogging is another key opportunity. Latin American cities can adopt and adapt decentralized, modular, and cost-effective technologies (e.g., small-scale anaerobic digesters, community composting) that are more suitable for local conditions, lower in capital cost, and can be implemented incrementally [138]. The growing digitalization of waste management through smart bins, route optimization software, and citizen engagement apps offers tools to improve logistical efficiency and transparency [139].

Finally, the development of integrated policy frameworks and market mechanisms is a critical enabler. Implementing extended producer responsibility (EPR) schemes for packaging can free municipal resources for organic waste management. Creating stable offtake markets for compost and biogas through public procurement for parks or mandating biofertilizer use in peri-urban agriculture can ensure economic sustainability. National and municipal "circular economy roadmaps," as seen in Chile and Colombia, provide the strategic vision and multi-stakeholder platforms needed to coordinate action [140]. By strategically addressing the barriers and harnessing these opportunities, Latin American cities can transform their OMSW management from a chronic challenge into a cornerstone of sustainable urban development.

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9. Discussion and Conclusions

The comprehensive review of the scientific literature (2020–2025) on the valorization of the Organic Fraction of Municipal Solid Waste (OFMSW) in Latin American cities reveals a rapidly evolving field, shaped by environmental urgency, circular economy aspirations, and the region's unique socio-economic realities. This discussion synthesizes key findings, analyzes emerging trends, identifies critical knowledge gaps, examines persistent challenges, and provides a critical comparison of valorization pathways, aiming to outline a viable roadmap towards sustainable and inclusive management systems.

9.1. Trend Analysis: Towards Integrated and Contextualized Valorization

The technological and management trajectory for OFMSW in Latin America is not converging on a single solution but on strategic integration and contextualization. Several clear trends are evident:

- From Centralized to Decentralized and Modular Systems: A synthesis of 14 case studies from medium-sized cities in Mexico, Colombia, and Brazil [38,43,78,138] reveals consistent evidence that decentralized or community-based systems (neighborhood-scale composting, modular digesters) offer advantages over centralized facilities in contexts characterized by limited capital, dispersed populations, and strong community organization. Seven studies quantitatively demonstrated that decentralized systems reduced collection-related GHG emissions by 15–35% compared to centralized alternatives [38,78], while also achieving higher participation rates in source separation (reported increases of 20–50% in four community-based programs [43,138]). However, the evidence is predominantly derived from pilot projects or programs operating at small scales (<5000 households), and robust long-term performance data (>5 years) remains limited. For metropolitan areas with high population density and concentrated waste generation, large-scale AD or MBT facilities continue to demonstrate superior economic viability in eight techno-economic assessments [87,93,106], though these studies acknowledge trade-offs in social inclusivity and community engagement. A systematic comparison between composting and anaerobic digestion shows that the GHG reduction ranges for these technologies are composting, 0.3–0.7 t CO_2-eq/t OMSW, and anaerobic digestion, 0.7–1.5 t CO_2-eq/t OMSW. This implies an increase in capital costs. Anaerobic digestion requires an investment 5–10 times greater than composting.
- From Linear Technologies to Hybrid "Treatment Trains": The literature evidences a shift away from reliance on a single technology. The synergistic combination of processes, such as AD coupled with composting, emerges as the most promising trend [81,82]. This hybrid approach maximizes resource recovery: AD treats wet, readily biodegradable waste (e.g., food waste) for energy (biogas) production, while composting stabilizes the digestate alongside lignocellulosic waste (e.g., yard trimmings) to produce a high-quality soil amendment. The synergistic configurations can achieve 10–30% higher overall resource recovery compared to standalone technologies, while resolving digestate management challenges. A technology suitability matrix should link each valorization pathway to specific urban contexts in Latin America. For example, composting is optimal for cities with agricultural peripheries and limited capital. Digital agriculture is suitable for metropolitan areas with energy demand and technical capacity. Hybrids are recommended where both conditions coexist. This integration solves key issues like digestate management and improves economic viability by diversifying end-products [83,86].
- From Waste Management to Circular Bioeconomy: The paradigm is evolving from merely "diverting from landfills" to "creating value from nutrients and carbon."

Comparing landfill gas capture and biological treatment shows that even with an efficient capture rate of 85–90%, landfilling untreated organic matter generates net GHG emissions 2–4 times higher than anaerobic digestion or composting of the source-separated organic fraction. Concepts such as urban biorefineries, where OFMSW is seen as feedstock for higher-value products like bioplastics (PHAs), organic acids, or biochar, are gaining traction [54,77]. Although still at pilot stages, these pathways represent the frontier of valorization and point towards deeper integration with local industrial and agricultural sectors.

- From Exclusion to Formal Inclusion of the Informal Sector: A distinct and crucial regional trend is the recognition of the indispensable role of the informal sector (waste pickers). Policies in Colombia and Brazil demonstrate that formalization and integration are not only a social justice imperative but also a strategy to improve system efficiency, increase recovery rates, and build legitimate governance [61,90,122]. The future of waste management in the region will be inclusive or ineffective.
- From Singular Environmental Analysis to Multidimensional Sustainability Assessment: The use of Life Cycle Assessment (LCA) has become standard for evaluating environmental performance [104,112]. The current trend is to couple LCA with Life Cycle Costing (LCC) and social assessments, employing Multi-Criteria Decision Analysis (MCDA) tools to support complex decision-making that balances environmental impacts, economic costs, and social benefits [42,107].

9.2. Policy Implications and Strategic Recommendations

Based on the evidence synthesized above, we derive the following policy recommendations:

5. Prioritize source separation as a non-negotiable prerequisite: The consistent finding across 22 studies [33,58,128] that feedstock contamination is the primary cause of treatment failure supports the recommendation that municipalities must invest in public awareness, infrastructure, and enforcement to achieve high-quality organic waste streams before investing in treatment facilities.
6. Adopt technology-neutral but context-specific targets: Given the evidence that optimal technology choice depends on local conditions (Table 3), national policies should establish diversion targets and environmental outcomes while allowing municipalities flexibility in technology selection, rather than mandating specific technologies.

9.3. Identification of Knowledge Gaps

Despite progress, significant research gaps persist, hindering optimal implementation:

- Gap in Standardized and Dynamic Data: As noted in Section 3.3, the lack of harmonized, periodic waste characterizations capturing socio-economic and seasonal variations remains a fundamental obstacle [32,33]. Low-cost methodologies and regional protocols are needed to generate reliable data for system design and modeling.
- Gap in Assessment of Decentralized and Community Systems: While there is an abundance of LCA and techno-economic studies for centralized plants, there is a critical shortage of rigorous sustainability assessments (especially the social pillar) of the decentralized, community-based, small-scale models more relevant to medium-sized cities [78,110].
- Gap in Technological and Governance Integration: More interdisciplinary research is needed on business models and governance mechanisms enabling the seamless integration of hybrid technologies (e.g., AD + composting) and formal/informal actors. How are public–private partnerships structured for decentralized systems? How are costs and benefits distributed in emerging circular value chains [47,67]?

- Gap in End-Market Development and Acceptance: Research has largely focused on conversion technology, but a significant gap exists in studying mechanisms to create and sustain markets for compost, digestate, and bioenergy. More work is needed on public procurement policies, quality standards adapted to local contexts, and consumer/farmer education strategies [63,130].
- Gap in Resilience and Climate Adaptation Assessment: Virtually no studies evaluate how OFMSW valorization systems in Latin America will perform under climate change impacts (e.g., water stress, extreme events) or how they can contribute to urban adaptation (e.g., soil improvement for water retention) [111].

9.4. Persistent Technical and Economic Challenges

The findings of this review underscore that challenges are systemic and interconnected:

- Technical and logistical aspects: Inefficient or non-existent separation from the source remains the main technical obstacle [128]. Contaminated OFMSW streams reduce the efficiency of biological processes, degrade compost quality, and increase pre-treatment costs. Furthermore, the high moisture and seasonal variability of Latin American OFMSW pose specific operational challenges, requiring technological adaptations (e.g., use of bulking agents) compared to designs imported from regions with drier waste streams [31].
- Economic–Financial: The high upfront capital investment for technologies like AD or MBT, contrasted with the low cost of landfill disposal (often not internalizing externalities), creates a critical financial barrier [129,134]. Immature markets for derived products (compost, biogas) generate uncertainty over revenue streams, discouraging private investment [130]. Medium-sized cities, with tighter budgets and lower borrowing capacity, are particularly vulnerable.
- Capacity-Related: A shortage of technical and managerial capacity at the municipal level to design, operate, maintain, and monitor complex valorization systems is prevalent [48,133]. This often leads to dependence on external consultants and the abandonment or malfunction of facilities after construction.
- Institutional and Policy-Related: Institutional fragmentation and policy incoherence between national, regional, and municipal levels, and across environmental, energy, and agricultural sectors, hinder the implementation of integrated strategies [65,131]. Weak enforcement and compliance of existing regulations (e.g., solid waste laws) allow linear practices to persist.

9.5. Critical Comparison of Valorization Methods

The superiority of one method over another is not absolute but contingent on the specific urban context (scale, waste composition, infrastructure, and market). The reviewed literature allows for a critical comparison:

Composting vs. Anaerobic Digestion (AD): Composting is technologically simpler, has lower capital and operational costs, and is more adaptable to small and community scales [69,70]. Its product (compost) is widely understood and can be directly integrated into urban agriculture and landscaping. It is superior in contexts where the priority is nutrient recovery for soils and community participation, and where waste is more fibrous (e.g., high yard waste content). Its main limitations are the lack of energy recovery and odor management challenges in densely populated areas. AD is superior when the goal is renewable energy recovery and the treatment of very wet, putrescible waste, such as food waste from markets and restaurants [71,72]. It offers greater climate benefit by capturing methane for energy use. However, it is more complex, costly, sensitive to feedstock quality, and requires post-digestate management. Its economic viability is strongly tied to the existence of incentives or markets for electricity/biomethane.

Biological Processes (AD–composting) vs. Thermochemical Processes (Gasification/Incineration): Biological processes are generally more suitable for Latin American OFMSW, given its high moisture and biodegradability. They preserve nutrients (N, P, and K) in forms useful for soil, closing the local biogeochemical cycle. They are more appropriate for the scale and capacities of most medium-sized cities. Thermochemical processes like gasification or pyrolysis require a refuse-derived fuel (RDF) with high calorific value and low moisture, which in turn demands costly drying and pre-processing of OFMSW [73,74]. While they offer high volume reduction and potentially high energy efficiency, they are technologically complex, capital-intensive, and raise concerns over air emissions. The literature suggests their niche in Latin America, if any, would be in very large metropolitan areas with advanced technical capacities and where energy recovery is an absolute priority over nutrient recovery [93]. For most cities, they are a less sustainable and less aligned option with the biological cycle of the circular economy.

Centralized vs. Decentralized Systems: Centralized systems (one large plant for the entire city) can achieve economies of scale in processing but incur high transportation costs, are vulnerable to single points of failure, and struggle with community engagement. They are superior for high-capital technologies (e.g., large-scale MBT, AD) in cities with high, concentrated generation and good road networks. Decentralized or semi-centralized systems (multiple smaller facilities) reduce transportation costs and carbon footprint, are more resilient, foster local participation, and can be adapted to the characteristics of different districts [38,138]. The reviewed literature indicates that for OFMSW valorization in Latin American medium-sized cities, decentralized or hybrid models are frequently superior, as they align better with financial constraints, urban topography, and the goal of creating short nutrient recycling loops.

In conclusion, this discussion demonstrates that the path towards sustainable OFMSW valorization in Latin America is not the pursuit of a "silver bullet" technology but the intelligent design of integrated systems. These systems must strategically combine biological methods (prioritizing hybrid over singular), adopt appropriate scales (favoring decentralization where viable), be grounded in reliable local data, be assessed through a triple sustainability lens, and, crucially, be built upon a foundation of inclusive governance that formalizes and empowers the informal sector. Future research must address the identified gaps, particularly in business models for short circuits, assessment of community systems, and the development of policy frameworks that translate circular economy principles into clear incentives and rules for all actors. Only then can OFMSW transition from being the emblematic problem of Latin American urbanization to becoming one of its key resources for sustainability.

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Abbreviations

The following abbreviations are used in this manuscript:

AD	Anaerobic Digestion
CE	Circular Economy
EPR	Extended Producer Responsibility
GHG	Greenhouse Gas
IWM	Integrated Waste Management
ISWM	Integrated Sustainable Waste Management
LAC	Latin America and the Caribbean
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MBT	Mechanical–Biological Treatment
MCDA	Multi-Criteria Decision Analysis
MSW	Municipal Solid Waste
NDCs	Nationally Determined Contributions
OFMSW	Organic Fraction of Municipal Solid Waste
OMW	Organic Municipal Waste
PHAs	Polyhydroxyalkanoates
PNRS	Política Nacional de Resíduos Sólidos (National Solid Waste Policy, Brazil)
PPP	Public–Private Partnership
RDF	Refuse-Derived Fuel
SROI	Social Return on Investment
TEA	Techno-Economic Analysis
WtE	Waste-to-Energy

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