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Municipal Solid Waste as a Renewable Energy Source: Evaluating the Potential for Sustainable Electricity Generation in the Minas Gerais Region in Brazil

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Abstract

Valorization of municipal solid waste (MSW) for energy represents a strategic alternative for developing countries, as it mitigates emissions, reduces pressure on landfills, and diversifies the electricity matrix. This study quantified the potential for electricity generation from MSW in the Jequitinhonha Valley, Minas Gerais, Brazil, using primary gravimetric characterization data, a method rarely employed in tropical areas. The identified composition showed a predominance of the organic fraction (47.6–73.3%), confirming the relevance of biological routes. The results indicated a consolidated potential of 106,640 MWh·year^{-1}, of which 94.7% was from biogas recovery and 5.3% from incineration. Almenara, one of the three locations analyzed, showed the highest potential (48,200 MWh·year^{-1}), followed by Diamantina (34,540 MWh·year^{-1}) and Capelinha (23,900 MWh·year^{-1}). The specific yields ranged from 0.33 to 0.53 MWh·ton^{-1} MSW and the per capita indicators from 1.01 to 1.49 MWh·cap^{-1}·year^{-1}. The climate mitigation potential reached 1.0 Mt of CO_2eq·year^{-1}. It is concluded that valorization in the Jequitinhonha Valley should prioritize biogas recovery, complemented by the incineration of rejects. The materialization of this potential requires advancements in infrastructure, selective collection, and socio-productive inclusion. This study provides evidence for public policies and contributes to the literature by demonstrating that valorization can boost energy transition and socio-environmental equity in developing tropical regions.

Keywords: circular economy; energy valorization; landfill biogas; sustainable energy transition

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1. Introduction

The increasing generation of municipal solid waste (MSW) represents a pressing challenge for contemporary societies, especially in developing countries, where population growth, unplanned urbanization, and limited infrastructure exacerbate the environmental and social impacts of inadequate MSW management [1–3]. By 2050, global MSW production

is estimated to exceed 3.4 billion tons per year, with approximately 33% of this waste still not being treated in an environmentally safe manner [4].

The scenario in Brazil is no different. Between 2022 and 2023, the daily generation of MSW increased faster than the population. In 2022, approximately 211 thousand tons of MSW were generated daily, totaling about 77.1 million tons for the year [5]. In 2023, the daily generation increased to approximately 221,000 tons, a rise of about 4.7% compared to 2022, while the Brazilian population remained relatively stable at around 211 million inhabitants [6].

Despite growing pressure on waste management systems, there has been limited progress in implementing policies for the energy valorization of waste, even with the incentives provided by the National Solid Waste Policy. Waste-to-Energy (WtE) technologies, such as anaerobic digestion, incineration, gasification, and landfill biogas recovery, have been explored globally for their potential to mitigate environmental impacts, reduce waste volume, and contribute to the diversification of the energy matrix [7–9].

Anaerobic digestion of the organic fraction of MSW is considered one of the most environmentally sustainable options, with a lower carbon footprint and the ability to generate biogas that can be used for decentralized electricity generation or biomethane [10,11]. While technically mature and widespread in developed countries, incineration requires high investments and rigorous emissions control systems [12,13]. Studies indicate [14–16] that, in Brazil, only biogas recovery in sanitary landfills is economically viable without direct subsidies, and public policies and institutional arrangements are necessary to enable other technological routes.

Despite the potential of WtE technologies, their implementation in developing countries faces significant challenges, including the heterogeneous composition of waste and high moisture and inert content, as well as economic, regulatory, and infrastructure issues [2,17]. Economic viability, in particular, requires incentives and support policies that convert the environmental benefits of these technologies into financial advantages, especially for options like anaerobic digestion and incineration, which are less economically attractive than biogas recovery in landfills without such support [18]. Including these sources in the distributed generation market can increase their financial attractiveness.

In regions marked by limited infrastructure, low population density, and socioeconomic vulnerability, these challenges become even more pronounced. This study addresses this gap by examining one such region, described in Section 4.1, as a representative case of the constraints and opportunities surrounding the adoption of WtE technologies under tropical developing country conditions. The analysis combines technical, environmental, and socioeconomic dimensions to assess the feasibility of sustainable energy recovery from municipal solid waste in settings where institutional capacity is often limited.

In this context, the high organic fraction of MSW, combined with the scarcity of decentralized energy solutions, makes the Jequitinhonha Valley a strategic territory for evaluating the feasibility of WtE technologies adapted to realities of low population density, limited infrastructure, and high social vulnerability. Despite this potential, a significant gap exists in the literature regarding the integrated assessment of MSW's technical and energy potential in the region, particularly considering different technological routes viable under local conditions. The absence of specific data and analyses hinders the formulation of customized and effective MSW management strategies for regions with similar socioeconomic and infrastructural profiles, thereby limiting the development of public policies and the implementation of projects that could enhance both environmental sustainability and local economic development. It is worth noting that, unlike most studies on modeling the energy potential of MSW, which rely on secondary data, this work incorporated primary gravimetric characterization data. The execution of this field stage represents a significant

methodological differential, as gravimetric campaigns are costly, require complex logistics, and depend on the cooperation of municipalities responsible for waste collection, which is not always feasible in regions with lower institutional capacity.

Given this, the present study aims to quantify the potential for sustainable electricity generation from municipal solid waste in the Jequitinhonha Valley, Minas Gerais, Brazil, by integrating a biological route (landfill biogas recovery) for the organic fraction and a thermal route (incineration) for waste with high calorific value. The proposal aims to provide technical and scientific support for formulating public policies and inter-municipal projects that focus on the energy valorization of waste, thereby contributing to regional development and environmental sustainability.

2. Results

2.1. Gravimetric Composition of Municipal Solid Waste

The gravimetric characterization of municipal solid waste (MSW) was conducted in the municipalities of Diamantina, Capelinha, and Almenara to determine the relative proportion of each material fraction and to support subsequent stages of energy recovery estimation. Table 1 presents the gravimetric composition of municipal solid waste. Only household waste was considered, excluding special, hazardous, electronic, and the miscellaneous fraction, whose heterogeneous composition makes energy quantification by the thermal route unfeasible.

Table 1. Gravimetric composition of municipal solid waste (%) in the municipalities of Diamantina, Capelinha, and Almenara (Jequitinhonha Valley, Minas Gerais, Brazil).

Material	Diamantina (%)	Capelinha (%)	Almenara (%)
Organic material	49.8	47.6	73.3
Chemical contaminant [2]	0.1	1.3	0.3
Biological contaminant [2]	10.6	11.6	5.5
Rubble	3.9	0.0	0.0
Rags and clothes	1.3	3.6	1.4
Miscellaneous	1.0	0.1	0.2
Metal	0.8	0.7	0.6
Glass	3.1	0.8	2.4
Soft plastic	3.8	16.7	3.6
Hard plastic	3.2	5.1	2.6
Paper and cardboard	18.4	8.4	6.2
Leather and rubber	1.9	2.2	2.9
Styrofoam	0.8	0.3	0.3
Aseptic packaging	1.1	1.7	0.1
E-waste (WEEE [1])	0.3	0.0	0.4
Total	100	100	100

[1] WEEE: Waste from Electrical and Electronic Equipment. [2] Chemical contaminant (or Chemical waste) includes small fractions contaminated with household chemicals (e.g., cleaning products, paints, or packaging with chemical residues), while Biological contaminant (or Biological waste) includes sanitary and small healthcare-type residues (e.g., diapers, sanitary pads).

The organic fraction predominated in all municipalities, with values of 49.8% in Diamantina, 47.6% in Capelinha, and 73.3% in Almenara. Biological contaminants ranged between 5.5% and 11.6%, while chemical contaminants accounted for less than 1.5% of the total. Dry recyclable materials, including paper and cardboard, plastics (both soft and hard), glass, and metals, were also identified in varying proportions. Capelinha recorded the highest percentages of soft plastic (16.7%) and paper/cardboard (8.4%). In Almenara, despite the high proportion of organic matter, significant quantities of leather

and rubber (2.9%), paper and cardboard (6.2%), and plastics (6.2% in total) were also recorded. Diamantina showed a more balanced distribution, with a high proportion of paper/cardboard (18.4%) and plastic waste (7.0%).

Figure 1 comparatively illustrates the relative proportions of the main fractions among the three municipalities, highlighting the contextual variations associated with the generation and destination of municipal waste. The observed differences reflect local consumption patterns, population habits, and the availability of collection and sorting infrastructure.

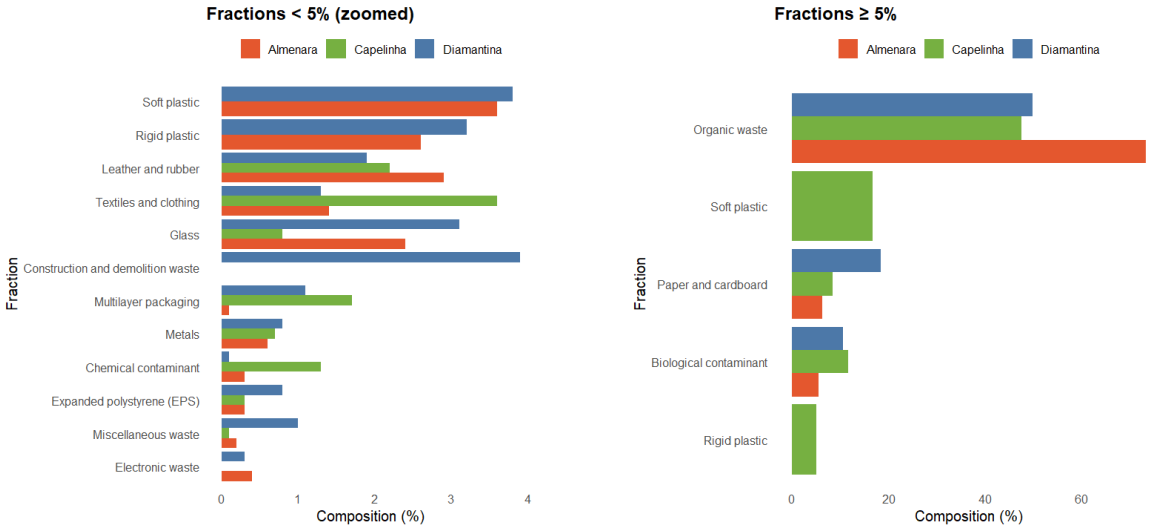


Figure 1. Distribution of municipal solid waste fractions (%) in three municipalities of the Jequitinhonha Valley, Minas Gerais, Brazil.

The data obtained formed the basis for the subsequent energy recovery analyses, with the fractions with thermal valorization potential selected as described in Section 4.4.

2.2. Estimated Waste Generation per Location

Table 2 shows population data, annual municipal solid waste (MSW) generation, and estimated per capita production for the municipalities of Diamantina, Capelinha, and Almenara. The annual generation data were provided directly by the municipal governments, based on operational records from municipal cleaning services. The per capita values were calculated from resident population estimates reported in the last census, conducted in 2022 and made available by the Brazilian Institute of Geography and Statistics (IBGE).

Table 2. Annual generation and per capita rate of municipal solid waste for three municipalities in the Jequitinhonha Valley, Minas Gerais, Brazil.

Municipality	Population	Estimated Annual Generation (Tons·Year^{-1})	Per Capita Generation (kg·Cap^{-1}·Day^{-1})
Diamantina	49,353	10,950.0	0.61
Capelinha	39,626	8212.5	0.57
Almenara	40,364	13,260.0	0.90

The data show significant differences among the analyzed municipalities. Almenara, with a population of 40,364 inhabitants, presented the highest annual waste generation (13,260.0 tons), resulting in the highest per capita rate among the municipalities: 0.90 kg·cap^{-1}·day^{-1}. Diamantina, with 49,353 inhabitants, generated approximately 10,950.0 tons·year^{-1}, corresponding to a per capita generation of 0.61 kg·cap^{-1}·day^{-1}.

Capelinha, in turn, with 39,626 inhabitants, presented the lowest annual generation (8212.5 tons) and the lowest per capita rate (0.57 $kg \cdot cap^{-1} \cdot day^{-1}$).

The observed differences in per capita waste generation among the three municipalities can be partially attributed to methodological inconsistencies in data acquisition. Almenara, which presented the highest per capita generation, does not currently operate a weighing scale for quantifying municipal solid waste. In this case, daily waste production is estimated by the service contractor based on national average parameters, which may not accurately reflect the local reality. Such estimation procedures can lead to systematic over- or underestimation of the actual waste mass, depending on local socioeconomic and infrastructural conditions. In contrast, Diamantina and Capelinha perform direct weighing, ensuring more reliable data. This highlights the importance of standardized and instrumented measurement systems in enhancing the reliability of municipal waste statistics and enabling fair comparisons across regions.

2.3. Energy Potential of the Organic Fraction (Landfill)

The energy valorization of the organic fraction of municipal solid waste through biogas recovery was estimated for the three municipalities of the Jequitinhonha Valley using the LandGEM model. The calculations considered the anaerobic decomposition of organic matter disposed of in landfills. Table 3 presents the energy and environmental indicators obtained for each location.

Table 3. Energy potential and avoided emissions for controlled landfills in the Jequitinhonha Valley, Minas Gerais, Brazil.

Municipality	Volume of CH_4 Captured (10^6 m^3) [1]	Recoverable Electrical Energy (MWh)	Specific Energy ($MWh \cdot Ton^{-1}$)	CH_4 Avoided (Tons)	Avoided Emissions (Tons of CO_2-eq) [2]
Diamantina	16.33	32,940	0.200	11,710	327,880
Capelinha	10.52	21,208	0.200	7540	211,120
Almenara	23.06	46,498	0.200	16,531	462,868

[1] Values represent cumulative results for the landfill operating period (2003–2024). [2] Avoided emissions calculated with GWP100 = 28 [19].

The electricity generation results varied among the evaluated municipalities. Almenara registered the highest generation potential (46,498 MWh), a value 41.2% higher than that observed in Diamantina (32,940 MWh) and 119.3% higher than in Capelinha (21,208 MWh). Diamantina presented an intermediate potential, with a value 55.3% higher than Capelinha. The specific energy, expressed in MWh per ton of disposed waste, was identical across the municipalities, with a value of 0.200 $MWh \cdot ton^{-1}$, a result of the standardization of the parameters adopted in the model.

The total volume of methane that can be captured was estimated at 49.91 $\times$ 10^6 m^3 for the three municipalities combined, distributed as 23.06 $\times$ 10^6 m^3 in Almenara (46.2% of the total), 16.33 $\times$ 10^6 m^3 in Diamantina (32.7% of the total), and 10.52 $\times$ 10^6 m^3 in Capelinha (21.1% of the total). These volumes correspond to the avoided methane masses of 16,531, 11,710 and 7540 tons for Almenara, Diamantina, and Capelinha, respectively, totaling 35,781 tons of CH_4 for the mesoregion.

In terms of climate mitigation benefits, avoided emissions totaled 1,001,868 tons of CO_2-eq, considering the 100-year global warming potential (GWP_{100} = 28). The distribution by municipality was 462,868 tons of CO_2-eq in Almenara (46.2% of the regional total), 327,880 tons of CO_2-eq in Diamantina (32.7%), and 211,120 tons of CO_2-eq in Capelinha (21.1%). The difference between the highest and lowest value of avoided emissions was 251,748 tons of CO_2-eq, corresponding to a variation of 119.3% between the municipalities.

Figure 2 graphically presents the distribution of recoverable electrical energy (bars) and avoided emissions (line) among the three municipalities, showing the direct proportionality between these two indicators in the evaluated scenarios.

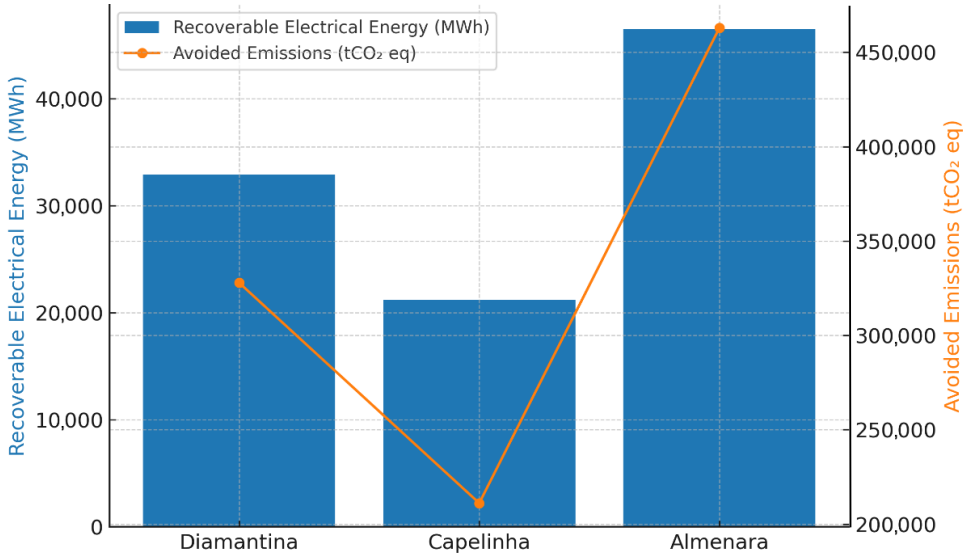


Figure 2. Recoverable electrical energy and avoided emissions from the capture and utilization of CH_4 in controlled landfills in the municipalities of Diamantina, Capelinha, and Almenara (Jequitinhonha Valley, Minas Gerais, Brazil).

The data obtained demonstrate significant variation in the energy potential among the studied locations, with Almenara showing the highest absolute and specific values for all evaluated indicators, followed by Diamantina and Capelinha in descending order.

2.4. Energy Potential of Dry Fractions (Incineration)

Table 4 presents the estimated results for electricity recovery via incineration of the combustible fractions of municipal solid waste (MSW) in the municipalities of Diamantina, Capelinha, and Almenara. The following materials with energy potential were considered: plastics (both soft and hard), leather and rubber, expanded polystyrene (also known as styrofoam), rags and clothing, and Aseptic packaging. Materials such as metals, glass, rubble, electronic waste, and the "miscellaneous" category were excluded from this estimation because they do not have relevant energy potential for incineration or pose an environmental risk, as described in Section 4.4.

Table 4. Estimated recoverable electrical energy via incineration of municipal solid waste, in the Jequitinhonha Valley, Minas Gerais, Brazil.

Location	Material	Fraction (%)	Mass (Tons·Year^{-1})	Energy (MWh·Year^{-1})
Diamantina	Plastics	7.00	766.50	834.78
	Leather + rubber	1.90	208.05	270.18
	Styrofoam	0.80	87.60	203.43
	Rags and clothes	1.30	142.35	130.49
	c packaging	1.10	120.45	161.94
Capelinha	Plastics	21.76	1787.04	1943.90
	Leather + rubber	2.20	180.68	234.63
	Styrofoam	0.30	24.64	57.21
	Rags and clothes	3.60	295.65	271.01
	Aseptic packaging	1.68	137.56	184.94

Table 4. *Cont.*

Location	Material	Fraction (%)	Mass (Tons·Year^{-1})	Energy (MWh·Year^{-1})
Almenara	Plastics	6.19	820.79	892.84
	Leather + rubber	2.94	389.84	506.26
	Styrofoam	0.34	45.08	104.70
	Rags and clothes	1.41	186.97	171.39
	Aseptic packaging	0.14	18.56	24.96

The calculations were based on the annual disposed masses of each fraction, obtained from the local gravimetric characterization, and their respective lower heating values (LHVs) selected from specialized literature. The LHVs adopted corresponded to the lower limits reported, reflecting a conservative approach. The total estimated energy was expressed in megawatt-hours per year (MWh·year^{-1}), considering a thermal conversion efficiency of 22%. All procedures are detailed in the Supplementary Materials.

In Diamantina, the total energy potential was estimated at 1599.82 MWh·year^{-1}, with a predominance of plastics (834.78 MWh·year^{-1}), followed by leather and rubber (270.18 MWh·year^{-1}) and styrofoam (203.43 MWh·year^{-1}). In Capelinha, the potential was significantly higher, totaling 2691.70 MWh·year^{-1}, with the plastic fraction being the highlight (1943.90 MWh·year^{-1}). Almenara, in turn, showed an intermediate potential, with 1700.14 MWh·year^{-1}, also dominated by plastics (892.84 MWh·year^{-1}).

Figure 3 graphically synthesizes the relative contribution of each fraction to the energy potential of each municipality, highlighting the relevance of the plastic fraction in the MSW energy profile.

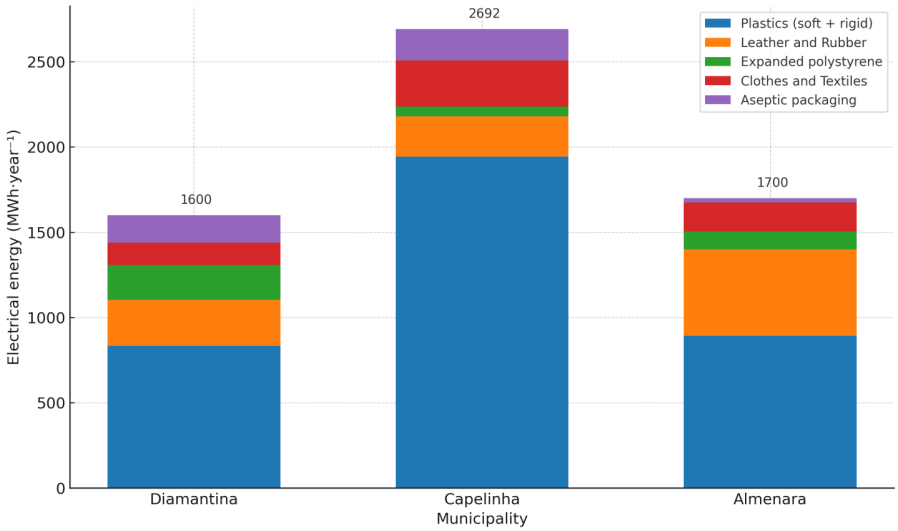


Figure 3. Relative contribution of the combustible fractions (plastic, leather/rubber, styrofoam, rags/clothes, and Aseptic packaging) to the estimated energy potential via incineration in Diamantina, Capelinha, and Almenara, Jequitinhonha Valley, Minas Gerais, Brazil.

2.5. Total Energy Potential and Comparison Between Routes

The total energy potential of municipal solid waste (MSW) in the Jequitinhonha Valley was consolidated for the two technological routes evaluated—biogas recovery in landfills and incineration of combustible fractions (Table 5). To ensure comparability among municipalities, the cumulative energy estimates obtained for landfills (2003–2024; Table 3) were converted into average annual values. The incineration potential was calculated from the annual generation of combustible materials (plastics, leather + rubber, textiles,

styrofoam, and aseptic packaging), considering their respective lower heating values (15–38 MJ kg^{-1}) and an electrical efficiency of 22%.

Table 5. Average annual consolidated energy potential of municipal solid waste in the Jequitinhonha Valley, Minas Gerais, Brazil.

Municipality	Landfill Potential (MWh·Year^{-1})	Incineration Potential (MWh·Year^{-1})	Total (MWh·Year^{-1})	MWh·ton^{-1} of MSW	Potential (MWh·Cap^{-1})	Biogas	Incineration
						% [1]	
Diamantina	32.94	1.60	34.54	0.35	1.01	95.4	4.6
Capelinha	21.21	2.69	23.90	0.53	1.02	88.7	11.3
Almenara	46.50	1.70	48.20	0.33	1.49	96.5	3.5
Regional Total	100.65	5.99	106.64	0.40	1.16	94.7	5.3

[1] Percentages represent the relative contribution of each route to the total for each municipality and region.

Table 5 shows that the region's total average annual energy potential reached 106.64 MWh × 10^3·$year^{-1}$, of which 100.65 MWh × 10^3·$year^{-1}$ (94.7%) originated from biogas recovery and 5.99 MWh × 10^3·$year^{-1}$ (5.3%) from incineration. Among the municipalities, Almenara exhibited the highest total potential (48.20 × 10^3 MWh·$year^{-1}$), followed by Diamantina (34.54 × 10^3 MWh·$year^{-1}$) and Capelinha (23.90 × 10^3 MWh·$year^{-1}$).

The specific energy potential of MSW ranged from 0.33 to 0.53 MWh·ton^{-1}, with Capelinha recording the highest value due to its larger share of combustible materials, mainly plastics and textiles. In contrast, Almenara showed the lowest value, consistent with its high organic content and dominance of the biogenic route. On a per capita basis, Almenara also presented the greatest potential (1.49 MWh·cap^{-1}), reflecting its larger waste generation rate.

Biogas recovery remained the predominant pathway, accounting for 95.4% of Diamantina's potential, 88.7% in Capelinha, and 96.5% in Almenara. Incineration contributed 4.6, 11.3, and 3.5%, respectively, underscoring how waste composition directly shapes the feasibility of each WtE route.

Figure 4 depicts the specific energy potential (MWh·ton^{-1}) for each technological route, highlighting both the regional predominance of biogas recovery and the relative increase in incineration share in municipalities with higher fractions of plastics and other high-calorific materials.

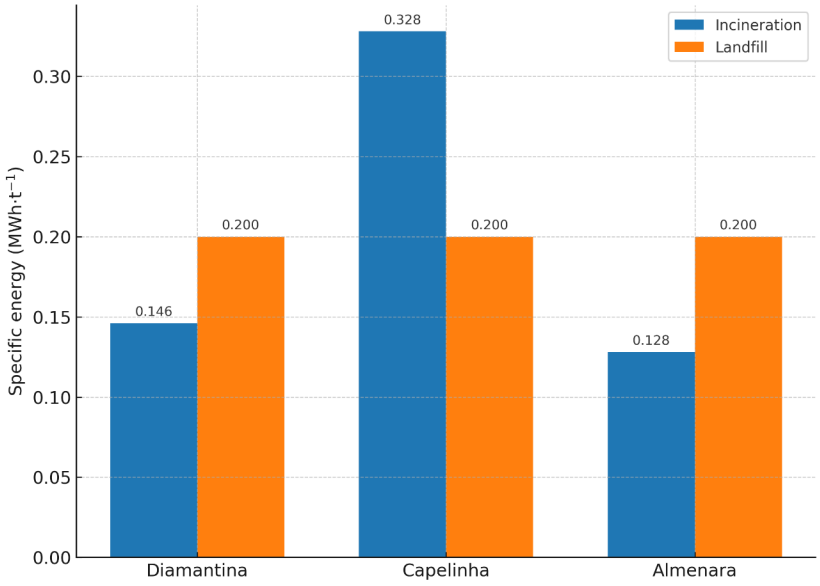


Figure 4. Specific energy potential (MWh·ton^{-1}) of municipal solid waste for localities in the Jequitinhonha Valley, Minas Gerais, Brazil.

3. Discussion

3.1. Waste Composition and Generation: Implications for Energy Valorization

The organic fraction was predominant in the municipal solid waste (MSW), varying from 49.8% in Capelinha to 73.3% in Almenara (Table 1). This pattern is typical of tropical regions, where organics represent 40–70% of MSW [20,21], aligning with the national average of ~51% [5]. Such a composition favors anaerobic routes, explaining Almenara's higher energy potential (48,198 MWh·year^{-1}, Table 5; 0.33 MWh·ton^{-1}).

The inter-municipal variations reflect structural differences in management and consumption. In Capelinha, the proportion of plastics reached 21.8% (soft + hard), in contrast to Diamantina (7.0%) and Almenara (6.2%) (Table 1). This result may be associated with the absence of waste picker cooperatives/associations and selective collection programs in the municipality. Without prior sorting, plastics are disposed of in the landfill, increasing their relative contribution to incineration in the modeled scenario (6.6% of the total potential, Table 5). In contrast, the low presence of metals (0.6–0.8%) and glass (0.8–3.1%) indicates limited material valorization, which is restricted by the coverage of selective collection (<10% in the region, IBGE [6]) and the prevalence of controlled landfills without waterproofing, leachate, and biogas systems.

As for waste generation, per capita rates varied from 0.57 kg·cap^{-1}·day^{-1} in Capelinha to 0.90 in Almenara (Table 2), both below the national average (1.047 kg·cap^{-1}·day^{-1}) in 2023 [5]. This difference is related to the socioeconomic profile (average IDHM 0.61) and the predominance of the rural economy. The higher value in Almenara may reflect the elevated organic fraction, the hot climate (25.3 °C, Aw), and possible collection failures. In humid environments, rapid degradation increases odors and leachates, requiring frequent collections and reducing the LHV of thermal routes [22]. Without data on density and frequency, this explanation should be considered hypothetical.

It is also important to note that methodological inconsistencies can affect the interpretation of per capita generation indicators. In Almenara, waste quantities are not directly weighed; instead, they are estimated by the contracted service company using national average parameters, which may not accurately represent local conditions. Such estimation procedures can lead to systematic uncertainties, which in turn influence both inter-municipal comparisons and the derived energy potential. This highlights the need for standardized weighing systems and transparent measurement protocols to improve the reliability of MSW data in Brazilian municipalities.

Regional evidence confirms these values: in Salvador, BA, for example, solid waste generation was estimated at 1.04 kg·cap^{-1}·day^{-1} [23], a value compatible with that observed in Almenara. Furthermore, studies conducted in the Northeast region of Brazil indicate averages of approximately 0.9–1.0 kg·cap^{-1}·day^{-1} [20]. Factors such as income and urbanization are the main determinants of generation [24], while climate indirectly affects the moisture and stability of the organic fraction [25]. This variation has an impact on the per capita energy potential (1.01–1.49 MWh·cap^{-1}, Table 5), suggesting that, in addition to energy, WtE projects can generate local socioeconomic benefits. In summary, the dominant organic fraction favors anaerobic routes, while the greater proportion of plastics in Capelinha highlights the importance of thermal routes. Differences in per capita generation amplify inequalities in absolute potential, reinforcing the importance of selective collection policies and WtE scenarios adjusted to the local reality.

3.2. Viability of Biogas Recovery

Biogas recovery from controlled landfills represents the main route for energy valorization in the Jequitinhonha Valley, totaling 100,650 MWh/year, which accounts for 96% of the regional potential. This performance is directly related to the high organic fraction of

municipal solid waste (MSW), which ranges from 47.6% to 73.3% (Table 1). The estimates, obtained using the LandGEM model with an average efficiency of 55.5% (Table 3), fall within the range reported for Brazilian landfills (48–68%) [26,27]. However, they are still subject to uncertainties related to critical parameters, such as the decay rate (k), which can alter the results by up to ±20% [28].

Almenara exhibited the highest absolute biogas potential, reflecting its high organic fraction (73.3%) and favorable climatic conditions (Aw climate, with an average temperature of 25.3 °C and annual precipitation of 873 mm; Section 4.1). These conditions favor anaerobic decomposition. However, the specific efficiency per ton of MSW was similar among the municipalities, with an average value of 0.200 MWh·ton^{-1} (Table 3). Still, the capture efficiency in controlled landfills remains lower than that obtained in biodigesters, which can achieve 70–90% methane recovery and produce 150–250 m^3 of biogas per ton of the organic fraction [29,30]. The adoption of this technology could increase the regional energy yield by 20–50%. In this context, community/municipal biodigesters are a promising alternative, integrating the organic fraction of MSW (and, when applicable, agricultural waste) into local family economy arrangements and services.

Evidence from tropical regions indicates payback periods between ~1 and 5 years for anaerobic digestion (AD) of the organic fraction of MSW, depending on the scale, the level of waste segregation at the source, and the revenue structure considered. In São Paulo (SP), de Oliveira et al. [31], registered a payback period of 1.01 years (cogeneration in a shopping center), while Alam et al. [32], in Bangladesh, reported ~2 years in a decentralized project, and Goh et al. [33], in a study conducted in Malaysia/Singapore, projected ~5 years in techno-economic analyses for AD plants in an urban context. These results support the economic viability of community/municipal biodigesters when there is selective collection of organics and local energy utilization.

However, in the specific context of the Jequitinhonha Valley, their implementation may face practical challenges related to limited technical expertise, the need for initial investment and regular maintenance, and the establishment of cooperative management models. These aspects do not compromise the technical feasibility of anaerobic routes but emphasize the importance of capacity building, financial support mechanisms, and community participation to ensure effective operation and continuity. When viewed at a regional scale, these decentralized systems would complement landfill biogas recovery, jointly enhancing methane capture efficiency and broadening the potential for greenhouse gas mitigation.

The climatic benefits of biogas recovery are significant, with a mitigation potential estimated at 1.002 Mt CO_2eq·year^{-1} (Table 3, GWP_{100} = 28), contributing to the achievement of the PNRS and Paris Agreement goals. However, locally controlled landfills (Section 4.5) have serious structural limitations, such as the absence of leachate drainage systems and waterproofing barriers, which can lead to fugitive emissions of 20–50% of the generated methane [34,35] and increase the risk of groundwater contamination, especially in humid regions. From an economic perspective, implementing capture systems in small-scale landfills requires investments of approximately US$5–15 million [36,37], with returns made viable by the distributed generation mechanisms established by ANEEL Normative Resolution N° 1.059/2023 [38]. Thus, although the route presents significant potential for mitigation and energy utilization, its implementation requires structural advances that prioritize the transition of controlled landfills to technical conditions more closely resembling those of sanitary landfills.

3.3. Viability of Incineration as a Complementary Route

Incineration of the combustible fractions of municipal solid waste (MSW) accounted for 5.6% of the regional energy potential (5992 MWh·year^{-1}), with Capelinha having the highest value (2692 MWh·year^{-1}) due to its high proportion of plastics (21.8%). Diamantina and Almenara recorded similar potentials (1600 and 1700 MWh·year^{-1}, respectively). The specific yields obtained (1.11–1.21 MWh·ton^{-1} of combustible fraction) are comparable to the values of 0.754–1.114 MWh·ton^{-1} reported by Gu et al. [39], for similar fractions.

The limited contribution of this route is a result of the low proportion of combustible materials in the total MSW (7.0–21.8% for plastics), a consequence of the high local organic fraction (47.6–73.3%). This characteristic is common in tropical regions, where the organic fraction reaches 70–75% in India [40] and similar values in other developing regions [41,42], in contrast to temperate countries, where combustible materials are predominant [43,44]. In Beijing [39], scenarios with food waste removal increased the potential from 0.336–0.439 MWh·ton^{-1} (unsegregated MSW) to 0.754–1.114 MWh·ton^{-1} (combustible fractions), demonstrating the impact of segregation. The conversion efficiency adopted in this study (22%) aligns with that of small-scale plants in developing countries [18] but remains lower than the 30% of large-scale plants [45].

According to Khan et al. [2], the economic viability of municipal solid waste incineration is limited without subsidies due to high initial investments and long payback periods. Waste-to-Energy (WtE) technologies are capital-intensive [46].

A feasibility study for an incineration plant with a potential of approximately 9,77 MW indicated an investment of 54,319 million USD and a negative Net Present Value (NPV) of −26,056 million USD, which demonstrates its economic unviability without incentives. Additionally, the investment costs for these plants can range from US$60,000 to US$130,000 per ton per day of processed waste [18].

Consequently, for incineration to be economically attractive, governmental incentives are necessary, such as an increase in the energy sales tariff or a reduction in investment, as well as policies that convert environmental benefits into financial advantages [47,48]. Furthermore, for small-scale plants (less than 100,000 tons·year^{-1}), significant investments for technological improvements in the steam cycle are generally not accessible [49].

In the Brazilian context, the regulatory framework imposes additional restrictions on the adoption of incineration. The National Solid Waste Policy [50] establishes a management hierarchy that prioritizes non-generation, reduction, reuse, and recycling, only permitting energy recovery as a complementary measure when the previous alternatives have been exhausted. At the same time, federal environmental standards [51] define rigorous technical criteria for the licensing of thermal treatment facilities, including atmospheric emission standards and continuous monitoring requirements. In this scenario, incineration should be understood as a technically viable alternative but is subject to strong regulatory and economic constraints. In the Jequitinhonha Valley, its eventual adoption would require integrated policies that include source segregation, the formation of inter-municipal consortia, and the creation of incentives capable of making regional-scale projects viable.

Although large-scale incineration plants are economically unfeasible under local conditions, recent developments in modular and integrated Waste-to-Energy systems (MIE) demonstrate viable small- and micro-scale solutions for non-recyclable fractions. Such modular units, operating at capacities of 2000–80,000 tons·year^{-1}, have been tested and gradually introduced in selected municipalities, mainly in Europe and Asia, as pilot or regional-scale applications aimed at decentralized waste management [52,53]. These systems reduce capital costs and shorten construction times, making them suitable for regional consortium applications in low-density areas such as the Jequitinhonha Valley.

3.4. Integrated Comparison Between WtE Routes and Regional Potential

The integrated analysis of the three municipalities evaluated in the Jequitinhonha Valley (Diamantina, Capelinha, and Almenara) suggests that energy valorization in the region is strongly guided by anaerobic routes, with a predominance of landfill biogas recovery (~94.4% of the total potential, or 100,650 MWh·year^{-1}) and a marginal contribution from incineration (5.6%, or 5992 MWh·year^{-1}) (Table 5), resulting in a consolidated yield of 106,642 MWh·year^{-1}. These values reflect the high organic fraction of municipal solid waste (47.6–73.3%) and the low content of dry combustible materials, factors that reduce the lower heating value and limit the attractiveness of thermal processes. Although restricted to three representative municipalities, this pattern is consistent with findings in tropical and developing countries, where the high-moisture composition favors biological routes and limits the economic viability of incineration [54,55]. Comparative efficiency data for waste-to-energy routes in similar tropical and developing regions are provided in Supplementary Table S1, supporting the consistency of the present findings.

The inter-municipal differences reinforce the influence of gravimetric composition and climatic conditions on technological choice. Almenara showed the highest absolute and per capita potential, a result of its high proportion of organic matter (~73.3%), associated with a hot and relatively dry climate that favors biological degradation. Capelinha, in turn, stood out for its greater relative contribution to incineration (~6.6%), due to the higher presence of plastics (~21.8%) in its waste fraction, despite having the lowest total yield among the three municipalities evaluated. Diamantina showed intermediate results, confirming the sensitivity of energy performance to compositional differences. This pattern is widely documented in the literature, where systems with wetter, organic-rich waste tend to favor anaerobic digestion, while drier compositions with a greater presence of solid combustibles increase the contribution of incineration [56].

It is also important to note that the expansion of recycling programs, particularly for plastics, would reduce the thermal energy potential while improving the overall environmental performance of the system. This trade-off reinforces the complementary role of incineration, restricted to non-recyclable fractions, within an integrated waste management strategy that prioritizes material recovery.

On a national scale, studies indicate that the high organic fraction in Brazilian municipal solid waste, generally greater than 50%, underscores the importance of anaerobic routes, especially in small and medium-sized cities with limited investment capacity in waste-to-energy plants [57,58]. This profile is consistent with patterns in developing countries, where the predominance of organic matter favors biological routes over incineration, in contrast to developed countries, where incineration predominates due to greater segregation and lower waste moisture content [59,60].

In light of this evidence, the segregation of the organic fraction for anaerobic digestion, associated with the incineration of combustible rejects, is configured as a strategy capable of expanding energy recovery and mitigating net greenhouse gas emissions. Case studies indicate that the removal of food waste can increase the specific electricity from incineration from ~0.34–0.44 to 0.52–0.68 MWh·ton^{-1}, reaching ~1.11 MWh·ton^{-1} in high-separation scenarios [39]. Life cycle assessments also indicate improved net environmental performance in "cascading" systems (hybrid waste-to-energy systems), although the gains depend on factors such as waste composition, segregation rates, and the electricity grid [61,62].

These findings suggest that integrating anaerobic digestion and incineration can serve as an energy transition strategy for regions with a high organic content in their waste, such as the Jequitinhonha Valley. By articulating technical gains in energy utilization with significant environmental reductions, this hybrid configuration highlights pathways to align waste management with sustainable energy and climate mitigation goals. Although

the results discussed are limited to three municipalities, they provide robust evidence that the mesoregion has the conditions to structure an energy valorization model adapted to its socio-environmental specificities.

3.5. Environmental, Socioeconomic, and Policy Implications

The results point to significant climatic benefits associated with the energy valorization of municipal solid waste (MSW) in the Jequitinhonha Valley. Biogas recovery in landfills accounts for the largest share of the regional potential, allowing for the avoidance of significant methane emissions. A total reduction of 1.00 Mt CO_2eq·year^{-1} is estimated for the three municipalities studied, which aligns with the proportionality observed between recovered energy and avoided emissions (Table 3). Life cycle assessment studies in developing countries confirm that capturing and utilizing methane in landfills represents one of the most effective routes for mitigating emissions in the waste sector [63,64]. This estimated mitigation potential is consistent with Brazil's National Methane Reduction Program [65], which prioritizes the recovery and energetic use of biogas from landfills and anaerobic digestion as key strategies for achieving the country's methane abatement targets in the waste sector. The quantified reduction of approximately 1.00 Mt CO_2-eq·year^{-1} in the Jequitinhonha Valley represents a proportional regional contribution to these national goals.

In terms of sustainability, this mitigation contributes to achieving sustainable energy goals and fulfilling the National Solid Waste Policy (PNRS), which establishes a management hierarchy and allows for energy recovery as a complementary measure. This guideline prioritizes biological routes and the judicious use of thermal alternatives [66].

On an environmental level, the transition from disposal areas classified as controlled landfills to conditions closer to those of sanitary landfills is a necessary condition to materialize the potential for methane capture and energy use. In all three municipalities, there is an absence of waterproofing, drainage, leachate treatment, and biogas collection systems. This situation increases the likelihood of fugitive emissions and risks to water quality. Studies have shown that structural deficiencies in landfills are common in low- and middle-income countries, compromising both energy utilization and environmental protection [67,68]. Thus, prioritizing investments in environmental control infrastructure, alongside the implementation of energy utilization systems, maximizes both climatic and sanitary benefits, thereby reducing environmental liabilities and future remediation costs.

The socioeconomic implications are equally relevant in a mesoregion with an average IDHM of 0.61 and limited urban infrastructure. The expansion of active selective collection programs and the organization of waste picker cooperatives and associations tend to create formal jobs and increase local income through the material valorization of paper/cardboard, plastics, metals, and glass, which is currently underutilized. Experiences in different countries suggest that the inclusion of waste pickers in formal recycling systems leads to gains in income, dignity, and an increased material recovery rate [69,70]. In parallel, community biodigesters can anchor short value chains (electricity/biogas for local uses, biofertilizers for family farming), thereby boosting vulnerable economies and alleviating municipal expenses related to transportation and final disposal, provided they are supported by adequate operational design and governance [71,72].

At an institutional level, inter-municipal arrangements are strategic for achieving economies of scale, especially in contexts of low population density and moderate per capita generation. The formation of consortia for shared solutions, from the sorting and logistics of the organic fraction to centralized plants for combustible rejects, is consistent with the framework of the PNRS and is already considered a preferential guideline for regional viability [73]. Additionally, combining continuous environmental education with quality selective collection tends to improve source segregation, reducing the moisture

content in the fraction destined for thermal routes and increasing energy performance when incineration acts as a complementary route, without losing focus on the core regional strategy, which lies in biological routes and the utilization of biogas, as evidenced by Mühlenhoff et al. [74] and Zhang et al. [75].

Regarding policy instruments, three fronts stand out. First, economic incentives (e.g., green credit lines, tariff mechanisms, and energy contracting) can be used to internalize positive externalities and reduce initial capital barriers, with a focus on distributed generation projects and solutions that are scalable for small and medium-sized municipalities. Second, inter-municipal partnerships for investments in critical infrastructure (biogas collection and capture systems; sorting centers; composting yards), which dilute fixed costs and standardize practices. Empirical evidence from MSW consortia in Brazil (multiple case studies) documents gains in scale and cost rationalization in service provision [72,76]. Third, strengthening local governance involves setting gradual goals for selective collection coverage and establishing quality criteria for recovered materials, while consistently articulating environmental education and the productive inclusion of waste pickers to align environmental and social objectives.

In summary, the results reinforce that energy valorization, anchored in biological routes and complemented by thermal solutions for combustible rejects, can serve as a lever for environmental and socioeconomic transition in the Jequitinhonha Valley, Minas Gerais. The materialization of these benefits, however, depends on an integrated package: adequate sanitary infrastructure, selective collection, socio-productive inclusion, continuous environmental education, and inter-municipal coordination under the normative umbrella of the PNRS. These elements, when combined, increase the likelihood of converting technical potential into regional climatic, energy, and social benefits.

3.6. Study Limitations and Future Perspectives

Although the results provide a solid basis for quantifying the WtE potential of municipal solid waste (MSW) in the Jequitinhonha Valley, the study has methodological and conceptual limitations that influence its interpretation. First, the gravimetric characterization was based on a single campaign during the dry season, which minimized immediate rainfall interferences but omitted seasonal variations in MSW composition. In tropical climates, the organic fraction and moisture can increase to relevant levels in the rainy season, reducing the LHV of combustible fractions and altering biogas emissions [77,78]. This omission may underestimate the climatic impact in municipalities like Almenara (Aw climate).

Furthermore, the models adopted conservative assumptions, including minimum LHVs (Table 6) and a capture efficiency of 55.5% in the LandGEM model, potentially underestimating the energy yield. The LandGEM model, widely used in inventories, assumes standard values for Lo and k that do not always reflect local conditions, introducing substantial uncertainties. This methodological limitation can lead to methane overestimations in controlled landfills, particularly when site-specific data for calibration are unavailable. The scope, limited to three representative municipalities, restricts generalization to the 51 municipalities of the mesoregion, ignoring heterogeneities in population density and consumption patterns. Future research should therefore expand the analytical framework to the regional scale, incorporating inter-municipal data on waste generation, composition, and management coverage to model cumulative energy and mitigation potentials. Such scaling would allow the quantitative evaluation of consortium-based scenarios, aligning with the PNRS guidelines and the inter-municipal integration strategy.

Finally, the technical–energy focus excludes economic (e.g., NPV) and social analyses (e.g., impacts on waste pickers), limiting holistic viability assessments.

These limitations open avenues for future research. Seasonal and multi-year sensitivity analyses, integrating climatic data from INMET (Brazilian National Institute of Meteorology), would refine biogas and LHV estimates. Hybrid models, combining LandGEM with IPCC Tier 2/3 approaches (emission inventory methodologies with a greater level of detail) or Life Cycle Assessment (LCA), could quantify environmental and economic trade-offs under scenarios with incentives (for example, the Brazilian national program Methane Zero or Federal Bill No. 3311/2023) [65]. Following IPCC [19] and UNEP [4], the renewable share refers exclusively to biogenic waste streams.

Perspectives include techno-economic assessments of community biodigesters for the co-digestion of MSW and agricultural waste, aiming for yields of 150–250 m^3 of biogas per ton and the production of biofertilizers for family farming [79,80]. Studies expanded to the entire mesoregion, incorporating Social Life Cycle Assessment (S-LCA), could support inter-municipal consortia and pilot projects aligned with Brazil's National Solid Waste Plan (2024–2040). These extensions would not only address regional gaps but also contribute to a sustainable WtE in global low-income contexts, promoting decarbonization and socioeconomic inclusion.

4. Materials and Methods

4.1. Study Area

The study was conducted in the mesoregion of the Jequitinhonha Valley, located in the northeast of the state of Minas Gerais, Brazil, approximately between the geographical coordinates 16°40′–18°00′ S latitude, and 42°30′–44°30′ W longitude. The region covers an area of about 50,000 km^2 and has an estimated population of 682,000 inhabitants [6]. It is characterized by high socioeconomic vulnerability, as evidenced by indicators such as the Municipal Human Development Index (MHDI), which has historically been below the national average (mean value of 0.61), and by a strong dependence on government social programs. The local economy is predominantly based on family farming and informal activities, with low industrialization and weak urban infrastructure.

These structural conditions are reflected in the management of municipal solid waste (MSW), which faces significant challenges, including the prevalence of open dumps, limited selective collection coverage, and inadequate institutional capacity to implement efficient waste treatment systems. In this context, the high organic fraction of MSW, combined with the scarcity of decentralized energy solutions, makes the Jequitinhonha Valley a strategic territory for evaluating the feasibility of WtE technologies adapted to regions characterized by low population density, limited infrastructure, and high social vulnerability.

To adequately represent the distinct parts of the Jequitinhonha Valley and its socio-environmental specificities, three municipalities were selected: Diamantina (upper portion), Capelinha (middle portion), and Almenara (lower portion) (Figure 5). The selection was based on territorial representativeness and socioeconomic diversity criteria, considering different contexts of MSW infrastructure and management across the valley.

According to estimates from the Brazilian Institute of Geography and Statistics (IBGE) [6], the populations of these municipalities in 2022 (the year of the most recent census) were 47,702 inhabitants in Diamantina, 39,626 in Capelinha, and 40,364 in Almenara. The local climatic conditions, which influence waste-decomposition processes, vary among the municipalities: Diamantina has a Cwb climate (temperature with dry winter and warm summer) according to the Köppen classification, with an average annual temperature of 19.2 °C and average cumulative precipitation of 1389 mm, while Capelinha and Almenara present an Aw climate (tropical with dry winter), with average annual temperatures of 21.8 °C and 25.3 °C, and average cumulative precipitation of 1015 mm and 873 mm, respec-

tively. Climatic data were obtained from the Brazilian National Institute of Meteorology (INMET) [81] and represent long-term climatological normals.

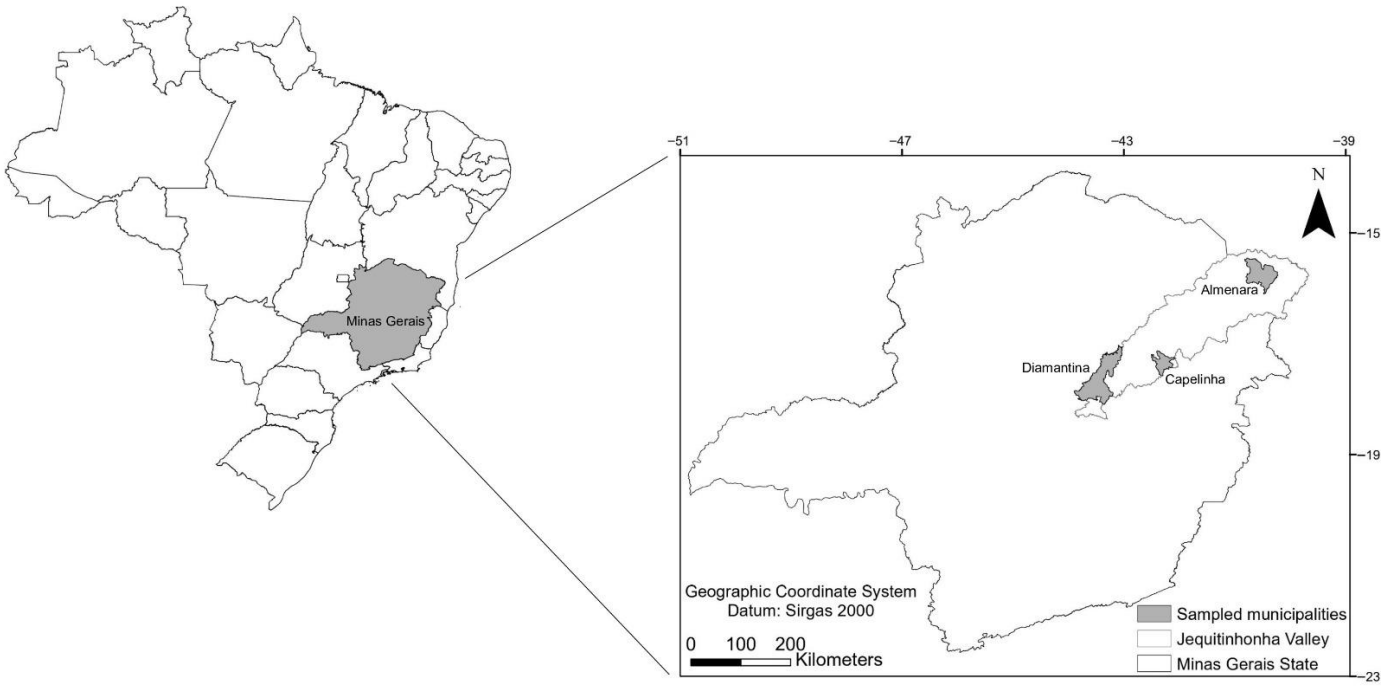


Figure 5. Location and territorial division of the Jequitinhonha Valley, Minas Gerais, Brazil, highlighting the sampled locations.

4.2. Gravimetric Characterization of Waste

The gravimetric composition of MSW was determined through field campaigns conducted in the three selected locations (Diamantina, Capelinha, and Almenara), following the procedures established by the Brazilian Technical Standard NBR 10007:2004 of the Brazilian Association of Technical Standards (ABNT) [82], which regulates the criteria for sampling solid waste in the country. This procedure represents a methodological differential compared to most studies on energy potential modeling, which rely on secondary databases, since gravimetric campaigns require substantial financial resources, a specialized technical team, and direct cooperation with the municipalities responsible for waste collection. The use of primary data, although limited to three municipalities representative of the mesoregion, enhances the reliability of the estimates by providing a more accurate reflection of the local conditions of MSW generation and composition.

In each municipality, a single sampling campaign was conducted between June and August 2025, corresponding to the dry season in the Jequitinhonha Valley, to minimize the influence of precipitation on waste composition and ensure comparability among datasets.

The daily samples, with a minimum mass of 200 kg, were collected at strategically defined points, with the support of the municipal environmental secretariats, covering regular collection routes and urban sectors with distinct socioeconomic profiles.

The collected waste was manually segregated into previously defined categories: organic matter, paper, soft plastics, rigid plastics, metals, glass, expanded polystyrene (Styrofoam), leather/rubber, rubble, biological and chemical contaminants, rags, aseptic packaging (Tetra Pak, multilayer paper cartons), and electronic equipment (E-waste). The gravimetric percentages of each fraction were calculated based on the total wet mass of the sample.

4.3. Estimation of Biogas and Electricity Generation in Controlled Landfills

The estimation of the energy recovery potential from the organic fraction of municipal solid waste disposed of in landfills was performed using the Landfill Gas Emissions Model (LandGEM v3.03), developed by the Environmental Protection Agency (EPA) [83]. This model assumes that biogas generation results from the anaerobic decomposition of organic matter and that the volume of methane produced follows a first-order decay equation over time.

The general Equation (1) used to estimate the annual volume of methane generated is presented below:

$$Q_{CH_4}(t) = \sum_{i=1}^{n}\left[k \cdot M_i \cdot Lo \cdot e^{-k\cdot(t-i)}\right] \quad (1)$$

where: $Q_{CH_4}(t)$ is the volume of methane generated in year t ($m^3 \cdot year^{-1}$); M_i is the mass of waste disposed of in year i (tons); Lo is the methane generation potential (m^3 of $CH_4 \cdot ton^{-1}$); k is the organic matter decay constant ($year^{-1}$); and $t - i$ is the time elapsed since the disposal of mass M_i.

The recoverable electrical energy from the captured methane was estimated based on the lower heating value (LHV) of the gas and the electrical conversion efficiency of the generation systems, according to Equations (2) and (3):

$$E_{electricity}(MJ) = Q_{captured} \cdot LHV \cdot \eta \quad (2)$$

$$E_{electricity}(kWh) = \frac{E_{electricity}(MJ)}{3.6} \quad (3)$$

where: $Q_{captured}$ is the volume of methane effectively collected in the landfill (m^3/year); LHV represents the lower heating value of methane ($MJ \cdot m^{-3}$); and e; η is the electrical conversion efficiency (%).

A methane capture efficiency of 55.5% and an electrical conversion efficiency of 33% were adopted, consistent with typical values found in installations with motor-generators coupled to biogas extraction systems, as used by Santos et al. [18] and Pin et al. [84], for example. The LHV of methane was set at 35.8 $MJ \cdot m^{-3}$. The methane generation potential (L_0) was considered to be 170 m^3 $CH_4 \cdot ton^{-1}$ of waste, and the decay constant (k) was 0.06 $year^{-1}$, which are widely used reference values for LandGEM model applications. The mass of waste disposed of annually, the duration of landfill operations, and the biodegradable fraction of the waste were estimated based on local data and the results of the gravimetric characterization performed in this study.

Although WtE processes are often associated with renewable energy portfolios, this study focuses on the biogenic fraction of municipal solid waste, primarily composed of food, paper, and other organic residues, which is regarded as renewable, in accordance with the IPCC [19] and UNEP [4]. Fossil-derived materials, such as plastics and rubber, were excluded from the renewable share; thus, the results represent low-carbon energy recovery rather than fully renewable energy generation.

4.4. Estimation of Electricity Generation via Incineration

The energy recoverable through incineration was estimated based on the combustible fractions of municipal solid waste that were not designated for anaerobic digestion. The following categories identified in the gravimetric characterization were considered suitable for incineration: plastics (soft and hard), leather and rubber, styrofoam, aseptic packaging, and rags and textiles.

Fractions such as metals, glass, rubble, and electronic waste were disregarded because they either do not have energy potential through incineration or pose an environmental risk.

Therefore, they are recommended for alternative routes such as recycling, co-processing, or safe final disposal.

The annual mass of each combustible fraction (M_f) was estimated by Equation (4):

$$M_f = U \cdot F_f \quad (4)$$

where: U represents the total mass of disposed MSW (t·year^{-1}); and F_f is the percentage fraction by mass of each combustible component, according to the gravimetry.

The lower heating values (LHVs) for each fraction were obtained from specialized literature (Table 6), based on studies applied to municipal waste from tropical regions with similar composition. All LHVs were considered on an as-received basis to maintain consistency with the masses obtained from the gravimetric analysis (wet basis).

Table 6. Lower heating values (LHVs) used for energy estimation from Municipal Solid Waste (MSW) via incineration.

Material	LHV (MJ·kg^{-1}) *	Source
Plastics (soft and hard)	17.8–47.5	[85]
Leather	12.5–21	[86]
Rubber	30–35	[87]
Styrofoam (expanded polystyrene)	38–41	[85,88]
Rags and clothes	15–18	[89,90]
Aseptic packaging	22	[91]

* In our study, we adopted a conservative approach, using the lowest LHVs.

The total calorific value of the mixture LCV_{total} was calculated by the weighted average:

$$LCV_{total} = \sum \left(LCV_f \cdot F_f \right) \quad (5)$$

Based on this value, the available thermal power (P) was estimated by the expression:

$$P = 24 \cdot 3600 \cdot LCV_{total} \cdot M_{total} \cdot \eta \quad (6)$$

where: M_{total} is the total annual mass of combustible waste (tons·year^{-1}); and η is the thermal conversion efficiency, set at 22%, according to Leme et al. [92], which is a representative value for incineration plants with energy recovery in small and medium-sized municipalities.

4.5. Landfill Characterization

The technical characterization of the controlled landfills in the three municipalities analyzed (Diamantina, Capelinha, and Almenara) was necessary to define the parameters used in the energy models, especially for the application of the LandGEM model. All locations have final disposal areas classified as controlled landfills. This means they are sites with periodic waste cover but lack adequate infrastructure for waterproofing, leachate drainage, or biogas collection. In this study, the energy potential calculations were applied to controlled landfills, recognizing that energy recovery under real conditions occurs in sanitary landfills due to significant losses in systems without capture infrastructure.

In Diamantina, the controlled landfill was implemented in 2003 and underwent structural modifications starting in 2020, with the opening of deeper trenches to optimize space utilization. The waste is covered daily with soil, but there is no leachate drainage or treatment system.

In Capelinha, the landfill is also classified as controlled, with over 20 years of continuous operation. Waste is covered daily with soil, but, as in the other municipalities, there are no active systems for leachate or biogas collection.

In Almenara, the landfill operates with weekly waste cover, using layers of soil. There are also no leachate drainage or biogas collection systems, and the operational typology is similar to that of the other municipalities. Due to its structural characteristics and the absence of sanitary infrastructure, the landfill is also classified as a controlled site.

5. Conclusions

This study evaluated the potential for sustainable electricity generation from municipal solid waste (MSW) in the Jequitinhonha Valley (Minas Gerais, Brazil), based on primary gravimetric characterization data—a methodological differentiator compared to analyses based solely on secondary data. The composition of the MSW showed a predominance of the organic fraction (47.6–73.3%), a characteristic of tropical regions, favoring the biological route of energy valorization.

The results indicated a consolidated energy potential of 106,640 MWh·year^{-1}, with 100,650 MWh·year^{-1} coming from landfill biogas recovery (94.7%) and 5990 MWh·year^{-1} from the incineration of combustible fractions (5.3%). Almenara showed the highest absolute potential (48,200 MWh·year^{-1}) and per capita potential (1.49 MWh·cap^{-1}·year^{-1}), followed by Diamantina (34,540 MWh·year^{-1}; 1.01 MWh·cap^{-1}·year^{-1}) and Capelinha (23,900 MWh·year^{-1}; 1.02 MWh·cap^{-1}·year^{-1}). The specific efficiency ranged from 0.33 to 0.53 MWh·ton^{-1} MSW, while the climatic benefits corresponded to approximately 1.0 Mt of CO_2eq·year^{-1}, considering only the avoided CH_4.

These findings reinforce the importance of prioritizing biological routes for energy valorization in regions with low population density and limited infrastructure, with incineration serving as a complementary measure. The materialization of the potential, however, depends on the transition from controlled to sanitary landfills, the expansion of selective collection, the socio-productive inclusion of waste pickers, and the formation of inter-municipal consortia. Future research should incorporate seasonal analyses, techno-economic modeling, and life cycle assessments, including hybrid scenarios with community biodigesters. Thus, the energy valorization of MSW can be consolidated as a catalyst for energy transition, climate mitigation, and socio-environmental inclusion in developing tropical regions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/recycling10060205/s1, Table S1: Comparative efficiency of electricity generation from municipal solid waste (MSW) in tropical and developing regions [18,39,93–96].

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Conflicts of Interest: The authors declare no conflicts of interest.

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