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# Assessment of Urban Solid Waste Management in the Ecuadorian Amazon Region

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**ABSTRACT**

*The increase of municipal solid waste poses a significant global environmental and public health challenge, particularly in sensitive regions such as the Ecuadorian Amazon, where infrastructure and management are limited. In order to inform evidence-based sustainable MSW policies, this study sought to characterize the MSW generated in La Joya de los Sachas city using an innovative, integrative approach that includes biogas energy modelling, community attitudes, and empirical trash characterization.. The study structured questionnaires (n = 384) to investigate domestic-level waste management behavior and environmental attitude. Subsequently, a physical characterization of MSW was conducted in 114 households and additional sources, including markets, businesses, and public cleaning services, resulting in a total of 1,372 samples. Our findings reveal that the city generates 14.54 tons of MSW daily (0.659 kg per inhabitant per day), with 67.46% consisting of organic waste and 15.52% recyclable materials. Despite 92.4% of households expressing a commitment to the environment, only 55.8% engage in source separation of MSW. Insufficient room and understanding are the primary obstacles to residual separation. But according to energy potential study, biogas could produce up to 956.58 MWh of electricity annually by 2035, underscoring its importance in future renewable energy plans. The high proportion of organic and recyclable waste without effective recovery highlights an urgent need to implement source separation strategies, environmental education, and energy utilization. To the best of our knowledge, this is the first study in the Ecuadorian Amazon to have connected MSW composition, community behavior, and renewable energy potential within a methodological framework.*

**Keywords:** *Municipal solid waste, Organic, Environmental education, Energy potential analysis*

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## INTRODUCTION

Globally, the annual generation of more than 2.01 billion tons of municipal solid waste (MSW) is a growing concern with significant environmental and public health consequences (WBG, 2018). Anthropogenic activities generate solid waste and debris daily, which accumulates as MSW and harms both flora and fauna. Rapid urbanization and population growth further compromise the MSW situation, as indicated by the daily global production of 0.74 kg per person, a rate expected to increase by 70% by 2050 (Kaza *et al*., 2018).

One of the primary challenges of MSW accumulation is its quantity and composition. These depend on the habits and cultural activities of residents and can vary considerably from region to region, complicating the collection, transfer, and sorting processes of advanced solid waste management (SWM) methods and technologies (incineration, gasification, and pyrolysis) (Khan *et al*., 2022). Understanding these global complexities underscores the diverse challenges faced at regional levels, particularly in areas such as Latin America and the Caribbean.

These areas face significant challenges in MSW management. Despite progress, the region still grapples with uncontrolled open landfills (33%) and low waste fraction recovery rates (below 4%), mainly due to the limited adoption of advanced waste management technologies, such as incineration or anaerobic digestion (Margallo *et al*., 2019). This means that these products are a serious hazard to the environment and human health in developing countries.

Nationally, waste generation has doubled in the last 20 years, reaching an average daily generation of 14.593 tons in 2023 for a population of 17.757 million, with each inhabitant contributing 0.9 kg per day. Of this total, 55% is organic waste (INEC, 2024) represents significant potential for recycling.

Municipal solid waste management (MSWM) is a critical component of the environmental management system; moreover, it is crucial for circular economy strategies. Achieving sustainability requires comprehensive knowledge of the sources and types of solid waste and residues, as well as data on their composition, production rates, disposal, and accumulation (Shahabuddin & Alam, 2022). In this regard, MSW characterization is key. Overall, this detailed knowledge helps MSW managers devise specific techniques to effectively and appropriately control different types of waste while mitigating their impact effects (Kiran *et al*., 2023).

The characterization of solid waste at the global, regional, and national levels increases in relevance due to changes in consumption habits and rapid technological advances. The evolution of MSW generation and composition reflects current demographic and economic trends (Chen *et al*., 2020).

MSW management has gained strategic importance in climate change mitigation efforts through renewable energy generation, notably biogas recovery (Kurniawan *et al*., 2022). Landfills are no longer considered mere waste disposal sites but have emerged as critical hubs for energy recovery through biogas capture and utilization (Guo *et al*., 2022). The International Renewable Energy Agency (IRENA) estimates that biogas produced in landfills could cover between 3% and 5% of global primary energy demand (Agency, 2020). While simultaneously reducing methane emissions, with 28 times the global warming potential of $CO_2$ over 100 years (Pheakdey *et al*., 2023). The environmental policies in the European Union, the United States, and other regions promote decarbonization through the use of non-conventional renewable sources such as biogas (IEA, 2024).

In this context, the integrated analysis of citizen perceptions, the physical characterization of solid waste, and the estimation of the potential for biogas generation in landfills represent a key tool for strengthening planning and decision-making in Amazonian territories. Cities like La Joya de Los Sachas, located in the Ecuadorian Amazon, face particular challenges due to their rapid population growth, limited technical infrastructure, and ecological sensitivity, which requires sustainable solutions adapted to their socio-environmental conditions.

This study develops a technical framework to optimize circular waste management systems by integrating three critical dimensions: (1) biogas energy recovery, (2) community participation through social inclusion, and (3) climate-adaptive resilience strategies. By generating empirical evidence from an active Amazonian community, the work enables data-driven policy formulation—transforming waste systems from disposal-focused operations to integrated resource recovery networks that align with regional socioecological realities.

## MATERIALS AND METHODS

*Study area*

La Joya de los Sachas, located in Ecuador's Francisco de Orellana province, serves as a representative case study of municipal solid waste (MSW) management challenges in the Amazon region **(Figure 1)**. According to the 2022 national census, this urban center has a population of 16,023 inhabitants (INEC, 2022). The city's waste management system depends entirely on a 13-hectare landfill situated 3 km from the urban center, which currently operates with five closed waste cells, one active cell, and one prepared but unoccupied cell.

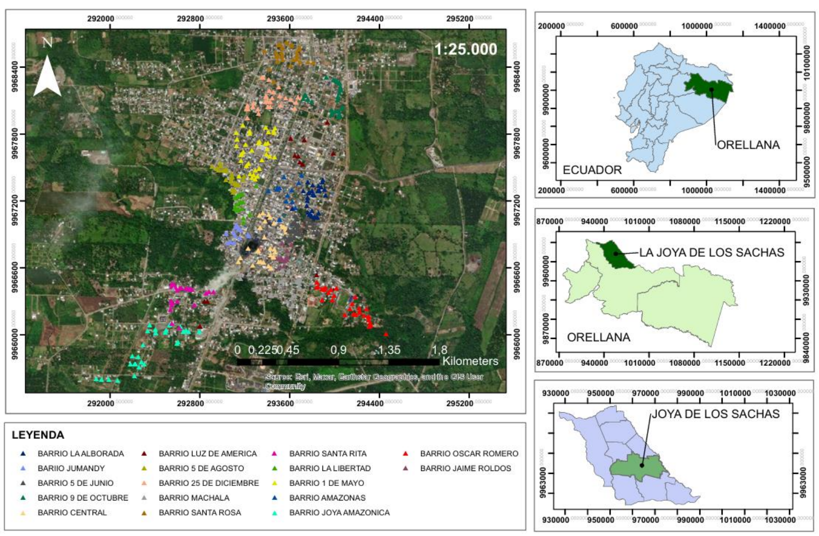


**Figure 1.** Map of the city of Sacha

Furthermore, at this landfill, the trucks transporting collected MSW are not weighed upon entry and lack official records on waste composition. This lack of data hinders the assessment of potential recovery and utilization opportunities for the disposed materials.

*Study design*

This study employed a two-stage methodology: first, assessing citizen perceptions of the existing Solid Waste and Residue Management System (SWRMS), including waste generation dynamics and openness to improvement initiatives, using a citywide household survey; and second, characterizing MSW from residential and non-residential sources (markets, commercial establishments, and street/public space cleaning services), while also estimating future landfill biogas generation under a business-as-usual scenario—assuming no source segregation or utilization of the biodegradable fraction.

*Sampling techniques*

*First stage: household surveys*

From February to May 2024, surveys were administered across 17 urban locations **(Figure 1).** The sample size was determined using the total number of households (7,550) reported in the 2022 national census (INEC, 2022). Applying a 95% confidence level, a 5% margin of error, and accounting for population variability, a representative sample of 384 households was selected.

*Second stage: MSW characterization*

Conducted from May to July 2024, this stage followed the methodology outlined by MINAM (2019), which prescribes a sample size of 114 households for populations of this scale. Additionally, waste characterization was performed at the town's two primary markets, San Francisco (Market 1) and Municipal (Market 2), with a representative sample of 110 commercial establishments. For street and public space sweeping services, the collected waste proportion was analyzed.

*Collection process*

Residential Sector: Four teams (each comprising eight personnel) collected waste over eight consecutive days. To avoid contamination from pre-existing waste, bags collected on the first day were discarded, ensuring data reflected only newly generated waste (MINAM, 2019). Daily collections occurred at 4:00 PM.

- Markets: Waste was collected over seven days at 4:30 PM from fixed points in both markets, with the daily weighing of all accumulated bags.
- Commercial and Public Spaces: Collections were conducted over five days (selected for peak generation periods) at 3:00 PM (commercial establishments) and 4:30 PM (sweeping services).

This systematic approach ensured representative sampling and data reliability across all waste streams.

*MSW characterization*

For households, commercial establishments, and public space sweeping/cleaning ser-vices, waste characterization was performed directly at the local landfill. For markets, characterization was conducted at their respective collection sites. At these locations, waste was spread daily on a 5 × 5 m plastic sheet. All accumulated bags were systematically separated, sorted, weighed, and recorded using calibrated scales, with measurements reported in kilograms (kg). Each bag was individually weighed and documented on a standardized sampling sheet.

The waste was sorted manually into various categories: cardboard, paper, PET plastic (bottles), HDPE plastic (bags), colored glass, clear glass, metal (beverage and food cans), Tetra Pak, food scraps, wood, pruning/garden waste, sanitary ware, and others. The "other" category comprised non-recyclable materials, including used napkins, wet paper, contaminated plastics/cardboard, sand, and electronic waste.

*Estimation of biogas generation*

Landfill biogas generation was estimated using LandGEM model v3.02 (U.S. EPA), a Microsoft Excel-based tool using first-order decay kinetics to calculate total biogas, $CH_4$, $CO_2$, and non-methane organic compound (NMOC) volumes (Osra *et al.*, 2021; Poma *et al.*, 2021; Lawal *et al.*, 2024).

The model consists of Eq. 1:

$$Q_{\mathrm{CH_4}} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} lL_{\circ}(\frac{Mi}{10}) e^{-\mathrm{k t}_{ij}} \tag{1}$$

Where QCH4 = annual CH4 generation, i = 1-year time increment, n = (year of the calculation) – (initial year of waste acceptance), j = 0.1-year time increment, k = CH4 generation rate (year−1), L0 = potential CH4 generation capacity (m3/Mg), Mi = mass of waste accepted in the ith year (Mg), t*ij* = age of the jth section of waste mass *Mi* accepted in the *i*th year.

The methane generation potential (L0) is almost exclusively a function of waste composition. Its value is estimated based on the carbon content of the waste, the biodegradable carbon fraction, and a stoichiometric conversion factor. If site information is available, the L0 value can be estimated using Eq. 2:

$$L_0 = 1000 \cdot MCF \cdot DOC \cdot DOC_F \cdot F \cdot \frac{16}{12} \tag{2}$$

where Lo = Methane generation potential (kg/tonne) MCF = Methane correction factor (fraction; default = 1.0) DOC = Degradable organic carbon (kg/tonne) DOCf = Fraction of assimilated DOC (IPCC, 1996 default = 0.77; IPCC, 2006 default = 0.50); F = Fraction of methane in landfill gas (0.5 default) 16/12 = Stoichiometric factor.

The methane correction factor (MCF) is influenced by both the depth of the landfill and its management conditions. According to Eggleston and Buendía (2006), the estimated MCF values vary depending on the operational characteristics of the site. For unmanaged landfills, the MCF is 0.4 when the depth is less than five meters and 0.8 when it is equal to or greater than five meters. In managed landfills, the factor increases to 0.8 for depths below five meters and reaches 1.0 for those exceeding five meters, reflecting the higher efficiency of controlled anaerobic degradation.

Semi-aerobic landfills exhibit intermediate values of 0.4 and 0.5 for depths below and above five meters, respectively, due to partial oxygen exposure that limits methanogenic activity. When the site conditions are unknown, conservative estimates of 0.4 for landfills shallower than five meters and 0.8 for those deeper than five meters are recommended, representing typical methane generation efficiencies under uncertain management or structural conditions.

DOC depends on the composition of organic waste, which is divided into 4 categories. It is calculated using Eq. 3.

$$\mathrm{DOC} = 0.4\mathrm{A} + 0.17\mathrm{B} + 0.15\mathrm{C} + 0.3\mathrm{D} \tag{3}$$

Where: A: Percentage of waste that corresponds to paper, cardboard, and textiles. B: Per-centage of waste that corresponds to garden waste or putrescible organic waste (excluding food). C: Percentage of waste that corresponds to food waste. D: Percentage of waste that corresponds to wood and straw.

DOCF represents the portion of organic matter converted into biogas. Its calculation de-pends solely on the temperature in the landfill's anaerobic zone, as shown in Eq. 4.

$$\mathrm{DOC_F} = 0.014\ \mathrm{T} + 0.028 \tag{4}$$

Where:

T: Temperature [ºC].

The values used for the parameters, along with others obtained from the MSW characterization, are presented in **(Table 1).**

This analysis covers the period from the start of the current accumulation cell's operation to the estimated closure year of the final disposal site (2024–2050).

**Table 1.** Parameters used in estimating biogas production in the landfill.

| Parameter | Valor |
|---|---|
| Fraction of MSW disposed at the dumpsite (%) | 79.37 |
| Methane Correction Factor | 1 |
| Degradable Organic Carbon | 0.126 |
| Fraction of DOC converted to gas | 0.7 |
| Methane generation rate ($year^{-1}$) | 0.267 |
| Potential Methane Generation Capacity ($m^3$/Mg) | 59 |
| Fraction of $CH_4$ in the Landfill gas | 0.6 |
| Recovered $CH_4$ | 0 |
| Oxidation factor | 0 |
| % MSW that is Paper & Textile | 5.91 |
| % MSW that is garden waste/other non-food organic waste | 1.57 |
| % MSW that is food waste | 64.94 |
| % MSW that is wood or straw | 0.67 |
| Average Temperature at the Landfill site (ºC) | 30 |

*Statistical analysis*

The analytical approach followed the three-component methodology developed by Fadhullah and Imran (2022). Descriptive statistics characterized the sociodemographic variables, waste separation practices, and household perceptions related to MSW management. Association between categorical variables were determined using the chi-square good-ness-of-fit test. Bivariate chi-square correlation analyses examined associations between sociodemographic factors and household perceptions regarding waste management. Logistic regression was selected to examine the association between waste separation practices and locality, gender, age, and household size as independent variables. The binary logistic regression analyses were performed using GraphPad Prism 9.0.

## RESULTS AND DISCUSSION

*Sociodemographic and background characteristics*

The survey captured valuable insights into the human dimension of waste management in La Joya de los Sachas. Among respondents, women represented the majority (N = 278), with participation spanning adults aged 18 to 70, a demographic cross-section reflecting the community's active engagement. Locality 16 had the highest number of surveyed households (N=48), followed by locations 11 (37), 5 (31), 15 (31), and a tie between 4 and 17 (30 each). We also found that family size mattered: nearly half of the families (46.45%, 203 of them) had 4-6 members, directly impacting their waste output. Chi-square tests confirmed significant differences across locality, gender, age, and household size ($p<0.05$), underscoring the sociodemographic nuances shaping waste practices (Botelho *et al*., 2023; Bulusu *et al*., 2023).

According to our research, improving MSW management necessitates putting in place inclusive environmental governance that blends public finance, citizen participation, and sustainability-focused laws. Previous research demonstrates that successful municipal programs typically incorporate education campaigns, training initiatives, and community outreach - all critical for fostering waste separation behaviors (Tapia *et al*., 2018; Wojtarowski *et al*., 2019). Equally important is formally integrating informal waste pickers while adopting both technical and social solutions (Bertanza *et al*., 2021; Khatiwada *et al*., 2021; Sondh *et al*., 2024).

*Citizen Practices and Perceptions on MSW Management*

We found a clear split in household waste separation: more than half (55.83%, 244 households) are already separating their waste at home. When residents do separate their waste, they mostly focus on recyclables. Plastic bottles are by far the most commonly sorted item (73.55%, 342 households), followed by plastic bags (42.58%, 198 households). After plastics, people tend to sort cardboard (33.76%, 157 households) and paper (28.6%, 133 households) **(Figure 2)**.

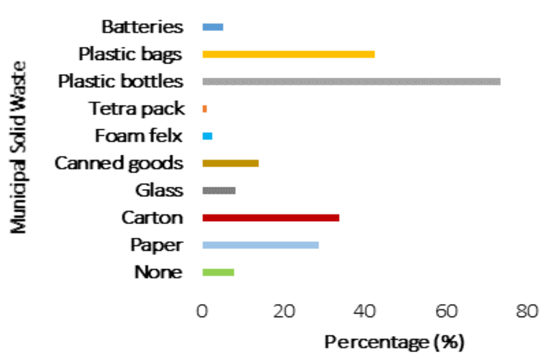


**Figure 2.** Types of municipal solid waste classified by the citizens of La Joya de los Sachas.

Notably, knowledge gaps persist: 52.40% of respondents felt poorly informed about waste management, contrasting with 35.23% who reported awareness. Despite this, 95.6% rated collection services as excellent to regular. A striking 92.45% expressed commitment to re-cycling, yet 35.69% cited low environmental awareness due to scarce education programs. Organic waste utilization remained limited (28.15%), repurposed as animal feed, and 25.4% composted, but 46.45% took no action. Street sweeping services received mixed evaluations, with 84.88% rating them as good to poor and only 3.20% as excellent (Negreiros *et al*., 2024; Omokunle, 2024).

Critical infrastructure shortfalls were evident: just 29.97% reported recyclers operating locally, and 81.92% noted insufficient containers for plastic bottles. Space constraints for storage emerged as the primary barrier to source separation (49.42% of households), pointing to logistical challenges beyond willingness (Dongmo *et al*., 2023; Lobach *et al*., 2023).

Evidence indicates that source separation programs coupled with selective collection and energy recovery technologies could potentially halve landfill dependence by boosting re-cycling rates (Malinauskaite *et al*., 2017). Crucially, waste segregation success hinges on public awareness and active participation (Hussein & Mona, 2018), underscoring the need for management plans that combine recovery strategies with education and policy frameworks.

*Relationship between sociodemographics and source separation*

A binary logistic regression analysis was used to determine the main sociodemographic characteristics of household trash separation practices. Locality, gender, age, and household size were all independent factors in the model **(Table 2).** The overall model was statistically significant ($p < 0.001$), indicating that the included predictors explained a significant portion of the variance waste separation practices.

**Table 2.** Logistic regression analysis of sociodemographic predictors of waste separation behavior

| Variable | | Parameter estimates | | | |
|---|---|---|---|---|---|
| | | **Estimate (B)** | **Standard error** | **Significance (p-value)** | **Odds ratio (Exp(B)** |
| **Intercept** | | 0.3404 | 0.5709 | 0.5510 | 1.405 |
| **Locality** | 1 | 0[a] | | | |
| | 2 | 0.6554 | 0.6795 | 0.3348 | 1.926 |
| | 3 | -0.4726 | 0.6571 | 0.4720 | 0.6234 |
| | 4 | 0.3183 | 0.6321 | 0.6146 | 1.375 |
| | 5 | 1.975 | 0.7406 | 0.0077* | 7.208 |
| | 6 | -0.2892 | 0.7526 | 0.7007 | 0.7488 |
| | 7 | 0.3692 | 0.6413 | 0.5648 | 1.447 |
| | 8 | 0.3963 | 0.6401 | 0.5358 | 1.486 |
| | 9 | 1.964 | 0.9272 | 0.0342* | 7.124 |
| | 10 | -0.2179 | 0.7616 | 0.7748 | 0.8042 |
| | 11 | -0.09534 | 0.6100 | 0.8758 | 0.9091 |
| | 12 | -0.2557 | 0.7006 | 0.7152 | 0.7744 |
| | 13 | 0.1995 | 0.6694 | 0.7657 | 1.221 |
| | 14 | 0.09919 | 0.6556 | 0.8797 | 1.104 |
| | 15 | 0.1648 | 0.6330 | 0.7946 | 1.179 |
| | 16 | 0.5489 | 0.6020 | 0.3619 | 1.731 |
| | 17 | -0.6892 | 0.6459 | 0.2859 | 0.5020 |
| **Gender** | Male | 0[a] | | | |
| | Female | 0.2741 | 0.2116 | 0.1952 | 1.315 |
| **Age** | <=30 | -0.5949 | 0.2785 | 0.0327* | 0.5516 |
| | 31-40 | 0[a] | | | |
| | 41-50 | -0.6712 | 0.3081 | 0.0293* | 0.5111 |
| | >50 | -0.3739 | 0.3100 | 0.2277 | 0.6880 |
| **Inhabitants** | 1-3 | 0[a] | | | |
| | 4-6 | -0.1609 | 0.2209 | 0.4664 | 0.8514 |
| | >6 | -0.4531 | 0.4070 | 0.2656 | 0.6357 |

**a:** Reference category for categorical variables.

The logistic regression identified several significant predictors of waste separation practices. Geographical location emerged as a strong determinant, with Locality 5 (OR = 7.208, 95% CI [1.759-33.940], p = 0.0077) and Locality 9 (OR = 7.124, 95% CI [1.32-57.34], p = 0.0342) exhibiting approximately seven-fold higher odds of [waste separation practices compared to Locality 1 (reference). These spatial disparities may reflect localized differences in infrastructure, policy implementation, or socioeconomic factors that warrant further investigation. Age also significantly predicted waste separation, with both younger (≤30 years; OR = 0.552, 95% CI [0.318-0.949], p = 0.033) and middle-aged (41-50 years; OR = 0.511, 95% CI [0.278-0.932], p = 0.029) respondents showing approximately half the odds of the reference group (31-40 years), suggesting potential generational or life-stage influences on waste separation practices (Ingle *et al*., 2023; Shaheen *et al*., 2023).

In contrast, gender (p = 0.195) and household size (p-values 0.466-0.266) showed no statistically significant associations, indicating these factors may be less relevant when ac-counting for other variables in the model. The intricate interaction of demographic and environmental factors influencing waste separation practices is highlighted by the combination of age-related patterns and large spatial impacts (Poornachitra *et al*., 2023; Yurievna *et al*., 2023).

*Association between respondents' background (location), MSW source separation practices, and perception of the SWRMS.*

Locations closest to the city center generally have a greater awareness of the SWRMS perception. Additionally, they are more appreciative of the usage of organic waste, pointing out that the more central districts have more recycling facilities.. However, the majority of respondents mention the lack of containers for depositing plastic bottles in all three locations **(Table 3).**

**Table 3.** Association between location, MSW source separation practice and respondents' perception of the SWRMS.

| | | Locality | | | | Residual separation | | |
|---|---|---|---|---|---|---|---|---|
| | | **Center** | **Media** | **Far** | **$\chi^2$ (valor p)** | **Yes** | **No** | **$\chi^2$ (valor p)** |
| **Level of knowledge about the solid waste management system** | Very informed | 3 | 0 | 1 | 16,769 (0.010) | 2 | 2 | 2,485 (0.478) |
| | Informed | 77 | 41 | 32 | | 91 | 59 | |
| | Poorly informed | 84 | 56 | 89 | | 124 | 105 | |
| | Unknown | 22 | 17 | 15 | | 27 | 27 | |
| **Rating of Solid Waste Collection Service in Your Sector** | Excellent | 13 | 9 | 4 | 63,897 (<0.001) | 11 | 15 | 4,943 (0.176) |
| | Good | 118 | 38 | 37 | | 115 | 78 | |
| | Fair | 45 | 63 | 82 | | 106 | 84 | |
| | Poor | 10 | 4 | 14 | | 12 | 16 | |
| **Level of environmental awareness regarding the management and Utilization** | High | 19 | 14 | 4 | 23,527 (<0.001) | 24 | 13 | 3,307 (0.191) |
| | Low | 79 | 23 | 54 | | 79 | 77 | |
| | Medium | 88 | 77 | 79 | | 141 | 103 | |
| **Commitment to Recycling and Environmental Protection** | Low | 22 | 3 | 8 | 11,563 (0.021) | 11 | 22 | 16,197 (<0.001) |
| | Medium | 92 | 56 | 77 | | 115 | 110 | |
| | High | 72 | 55 | 52 | | 118 | 61 | |
| **Rating of Street Sweeping and Public Space Service in the City** | Excellent | 8 | 3 | 3 | 124,067 (<0.001) | 10 | 4 | 13,114 (0.011) |
| | Good | 125 | 16 | 42 | | 109 | 74 | |
| | Fair | 36 | 57 | 57 | | 67 | 83 | |
| | Poor | 17 | 16 | 5 | | 23 | 15 | |
| | No service available | 0 | 22 | 30 | | 35 | 17 | |
| **Utilization of Organic Waste Generated at Home** | Composting | 55 | 21 | 35 | 18,021 (0.001) | 97 | 14 | 126,934 (<0.001) |
| | Animal feed | 52 | 22 | 49 | | 91 | 32 | |
| | Not used | 79 | 71 | 53 | | 56 | 147 | |
| **Recycling centers near your home that buy recycled materials** | Yes | 81 | 27 | 23 | 65,520 (<0.001) | 81 | 50 | 3,524 (0.172) |
| | No | 62 | 70 | 106 | | 130 | 108 | |
| | unknown | 43 | 17 | 8 | | 33 | 35 | |
| **Containers near your home for depositing recycled plastic bottles** | Yes | 63 | 3 | 13 | 56,515 (<0.001) | 53 | 26 | 4,952 (0.026) |
| | No | 123 | 111 | 124 | | 191 | 167 | |
| **Factors Making Waste Sorting Difficult at Home** | Lack of space for containers | 83 | 66 | 67 | 11,308 (0.079) | 127 | 89 | 10,972 (0.012) |
| | Wasting time sorting | 30 | 17 | 24 | | 27 | 44 | |
| | Lack of knowledge of how to recycle | 53 | 19 | 24 | | 58 | 38 | |
| | Lack of knowledge of the benefits of recycling | 20 | 12 | 22 | | 32 | 22 | |

Regarding waste separation **(Table 3)**, a significant relationship was found between commitment to recycling and environmental protection (16.197; <0.001). The use of organic waste generated at home (126.934; <0.001), the availability of containers for recyclable plastic bottles near their home (4.952; 0.026), the rating of street and public space sweeping services (13.114; 0.011), and factors that make it difficult to sort waste at home (10.972; 0.012) all showed a similar relationship. The results indicate that localities closer to the city center have a greater commitment to MSW management.

Respondents who engage in waste separation processes are more committed to recycling, and they also utilize organic waste for composting and animal feed. However, most respondents point out that lack of space is the main limitation for waste sorting at home.

*MSW characterization*

To address this gap, a total of 1,372 samples were collected during the evaluation period, distributed between residential and non-residential sources. We estimated a generation of 14.54

tons of MSW daily in the city, with each inhabitant contributing an average of 0.659 kg. Similarly, the total annual production is 5,305.61 tons.

Residential areas contributed the majority of MSW in the year (3,854.09 tons) and in shop-ping centers (1,119.70 tons). Regarding markets and cleaning sweeping services, the determined production was lower by 213.41 and 118.41 tons, respectively (Aleidi *et al*., 2022; Daivasigamani *et al*., 2022).

Our MSW characterization revealed a per capita generation rate of 0.659 kg/inhabitant/day, consistent with studies from Orellana province (Poma *et al*., 2025), and the Amazonian city of Puyo (Cazares *et al*., 2024). Similar findings emerged from research in Ecuadorian small towns (0.613 kg/inhabitant/day; Villa-Achupallas (2024), reflecting characteristic waste generation patterns in Amazonian communities.

*Organic solid waste*

The organic fraction represents the highest percentage of generation in the study area, accounting for 67.46% (9.81 tons per day) and a total annual production of 3,557.63 tons. Across all generation sources studied, both residential and non-residential, this fraction accounts for more than 65%, with markets standing out as the highest generation points in terms of individual percentages. In terms of total quantity, residential sources present the highest production value with 755,13 tons, followed by markets with 184,38 tons and cleaning services with 83,67 tons.

Organic waste dominated the waste stream at 67.46%, mirroring trends in nearby cantons (58.44-63.12%) (Poma *et al*., 2025). This pattern gives the region's semi-rural character and agricultural economy favoring fresh food consumption over-packaged goods. While matching Latin American averages (55%) (CEPAL, 2021; INEC, 2024), this percentage declines with national income levels, dropping to 33% in high-income countries (Kaza *et al*., 2018).

*Recyclable solid waste*

The total daily amount of recyclable waste generated in La Joya de Los Sachas is 2.26 tons, representing 15.52% of total production (823.88 tons per year). This fraction is composed of the following types: cardboard, paper, PET plastic (plastic bottles), HDPE plastic (plastic sleeves), colored and clear glass, metal (beverage and canned food cans), and Tetra Pack.

The annual total production of these materials resulted in 219.29 tons of HDPE plastic, 207.45 tons of cardboard, 114.99 tons of paper, 72.55 tons of clear glass, and 67.44 tons of PET plastic. Other materials, such as colored glass, metals, and Tetra Pack containers, showed marginal generation.

On the other hand, comparing the production percentages of each type of waste by generation source, the highest values were established in market 2 for cardboard at 67.35% and PET plastics at 21.77%; the residential source generates the highest percentage of paper (15.52%) and HDPE plastics (30.74%); the commercial source generates the highest amount of glass 1 (colored) with 10.15%, while glass 2 (transparent) is generated mainly by the sweeping and cleaning service. Regarding metal and tetra pack, market 1 is the largest generator with 10.68% and 12.82% respectively **(Figure 3).**

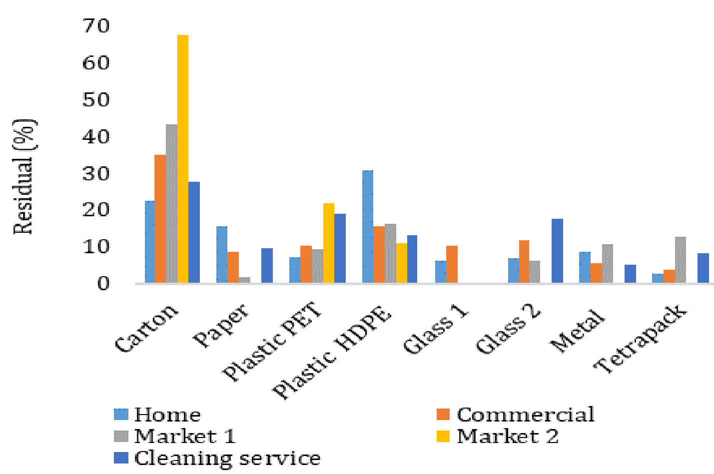


**Figure 3.** Percentages of MSW production by source in La Joya de los Sachas. Each bar represents the per-centages of waste production by source: blue for residential, orange for commercial establishments, lead for municipal market 1, mustard for municipal market 2, and light blue for sweeping and cleaning, with a 95% confidence interval. Recyclable waste includes PET plastic - plastic bottles, HDPE plastic - plastic bags, glass 1 - colored glass, glass 2 - clear glass, and metal - beverage and canned food cans.

The 15.52% recyclable fraction fell below Ecuador's national average 20.6% (INEC, 2024), likely reflecting lower consumption of processed goods in small municipalities. Plastic (11.4%), cardboard (5.2%), and paper (4.1%) comprised most recyclables. Enhancing the recovery of these materials could advance circular economy goals while improving liveli-hoods for informal recyclers - a crucial step given Ecuador's current 4% recycling rate (Hidalgo *et al*., 2023).

The substantial loss of recyclable materials' recovery potential when combined with organic and sanitary waste is a major challenge in MSW management. Research shows that 25–40% of recyclables become contaminated in non-segregated waste (Margallo *et al*., 2019), which is especially problematic in Ecuador's rural and Amazonian regions with inadequate infrastructure for selective collection (Chamorro *et al*., 2023). Applying a conservative 30% contamination estimate to La Joya de los Sachas' recyclable waste stream suggests ap-proximately 277 metric tons of valuable materials become unrecoverable annually due to current management practices.

The contamination problem persists even in advanced recycling systems. The U.S. EPA reports a 25% rejection of materials placed in recycling bins due to contamination or im-proper sorting (Esteban & Quesada, 2022). This figure represents an economic and environmental loss, with in-creased pressure on the local landfill reducing its useful life, and higher generation of greenhouse gas emissions. However, municipalities implementing kerbside waste-sorting programs demonstrate significantly lower rejection and contamination rates in recycling streams. This enhanced material quality enables more efficient diversion to high-value recycling processes, thereby improving overall circularity in waste management systems.

*Waste*

In this study, any materials not reused or recovered, including sanitary products and other discarded items, were classified as waste within the investigated location. This fraction represents 17.40% of the total. There is a sizable portion of these products that may enhance the quantity of recyclable waste if they were sorted effectively at the source. This fraction should ideally be the only kind of MSW to arrive at the final disposal location.

*Estimated biogas production potential at the landfill*

The absence of source-segregated waste collection in the study area creates a fundamental barrier to sustainable waste management. Without proper classification at generation points, valuable biodegradable materials become commingled with general waste streams, eliminating opportunities for recovery or beneficial reuse before landfill deposition. A viable option in this area is the use of generated biogas, which contributes to the circular economy and reduces greenhouse gas emissions.

According to the results obtained with the LandGEM model, the total estimated biogas production in 2025 would be 1,23 x 105 m3, which in turn has a potential electricity generation of 259.98 MWh/year. The estimate could represent the annual consumption of 14% of households in the area, considering an average consumption per household of 0.143 MWh/year.

In 2035, which is the year in which the greatest biogas generation would occur, a value of 4,53 x 105 m3 would be reached (an increase of 368%) **(Figure 4)**, which would allow an electrical generation capacity of 956.58 MWh/year.

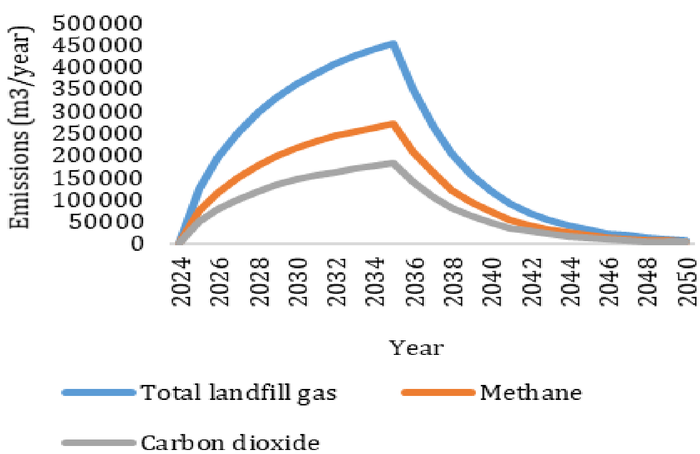


**Figure 4.** Total estimate of biogas and methane emissions in m3/year for the Joya de los Sachas landfill using the LandGEM model for the years 2024 - 2150.

Landfill biogas production potential is influenced by three key factors: environmental conditions (particularly precipitation, temperature, and humidity) (Poma *et al.*, 2025), operational practices including waste cell coverage and gas capture systems (Ruoso *et al.*, 2022), and waste composition dynamics (Machado *et al.*, 2021). The warm, wet conditions of Ecuador's Amazon and coastal regions create particularly favorable conditions for biogas generation.

Our study identified a maximum biogas generation potential of 956.58 MWh/year for La Joya de los Sachas. However, other Ecuadorian cities demonstrate even higher potential, with Puyo capable of 3,687 MWh/year (Cazares *et al.*, 2024), Machala 15,608 MWh/year, and Guayaquil an impressive 732,235 MWh/year (Poma *et al.*, 2025). This renewable energy potential could satisfy up to 10% of local electricity demand in waste-producing communities (Barragán *et al.*, 2020), while simultaneously advancing circular economy objectives and reducing greenhouse gas emissions.

## CONCLUSION

Organic waste forms the bulk of the urban solid waste stream at 67.46% in La Joya de los Sachas, which includes food scraps, wood, and yard garbage. While this valuable share has immense possibilities for composting or animal feed production, most remains unutilized due to inadequate source separation, lack of infrastructure, and absent recovery schemes. This is not only lost resources but also lost opportunities for reducing landfill pressure as well as sustainable waste management. Our report determines that 15.52% of waste generated is recyclable material, but much gets lost irretrievably due to contamination in mixed collection schemes. The absence of segregated collection streams, coupled with sparse public education, exacerbates this loss. Contributing to the issue, the unavailability of collection points, local recycling facilities, and proper containers jeopardizes successful material recovery. These findings underscore the need for improved infra-structure, welcoming policies, and legal incorporation of informal waste collectors into the system.

There is high biogas production potential in the municipal landfill with peak capacity estimated at 956.58 MWh/year by 2035—sufficient to produce about 14% of household electricity demand. However, this renewable energy source is nearly untapped. A shift to sustainable waste management would entail an interdisciplinary approach comprising energy recovery technologies, widespread environmental education, effective source separation programs, and active community involvement. An integrated approach in a model of circular economy would enhance territorial resilience and ensure environmental sustain-ability in the long run.

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