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REGIONAL CASE STUDY

Household waste generation, composition and determining factors in rapidly urbanizing developing cities: case study of Santa Cruz de la Sierra, Bolivia

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Abstract

Detailed information about waste generation rates, composition, and their influencing factors, is essential for sustainable municipal solid waste (MSW) management systems. While detailed waste characterization studies have been regularly conducted in industrialized countries for decades, they are still incipient and limited in scope in developing countries. Among all MSW streams, household waste (HW) represents a major fraction in developing countries with a distinctive influence on urban life-quality. This study conducts a HW characterization study in Santa Cruz, a rapidly urbanizing city of Bolivia, to (i) estimate HW generation rates and composition; and (ii) identify the main factors that explain variability in these rates. This is achieved through waste sampling and household surveys, manual component separation, and statistical analysis using correlations and multiple linear regressions. Results estimate a median waste generation rate of 0.548 kg/capita/day and a mean generation of 0.711 kg/capita/day for the whole city. Household size, household head (HH) education, children in the family and a kiosk in the household, are the main determinants of waste generation rates. Waste composition is comparable to other developing cities, with a relatively higher fraction of organic waste and fine residue, possibly due to context-specific characteristics of the urbanization process of the city.

Keywords Municipal solid waste · Household waste · Waste generation · Developing countries · Waste characterization

Introduction

Household waste (HW) is a major component of municipal solid waste (MSW). Changes in production and consumption patterns in the last decades have resulted in a mix of variate components including e-waste and hazardous waste, primarily generated through household consumption and secondarily by relevant livelihood activities [1, 2]. In developing countries, HW represents the largest fraction of MSW, accounting from 50 to 80% of the total amount of MSW generated [3]. The adequate management of HW influences greatly urban quality of life, as deficient practices have been linked to respiratory, gastroenterological and vector transmitted diseases [4–8], as well as landscape degradation and increased crime [9, 10]. Thus, the rapid increase in household waste generation rates (HWGR) and the shifts in its composition pose various challenges, especially in developing and rapidly urbanizing cities [2, 11].

Many factors affect household waste generation rates (HWGR) and composition. While there is a general agreement that income affects waste generation and composition

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at the country level [12], studies at the household level have provided mixed results. For example, some studies have found direct and strong correlations between household income levels (or proxy variables) and HWGR [13, 14], while in other cases these correlations have either not been found or not been statistically significant [3, 15–18]. Other factors typically identified as affecting HWGR include household size [19, 20], family type [21], age [22], education [20, 23], environmental awareness and dwelling characteristics [24].

Determining waste generation rates and characteristics, and the underlying factors affecting them, is essential for the planning of integrated sustainable solid waste management[1] systems [25–27]. For example, infrastructure and operations' design, as well as resource prioritization, rely on accurate information about rates, composition, geographical distribution, and trends over time, among others [28]. To obtain this information municipalities must conduct waste characterization studies periodically and comprehensively covering all relevant sources. However, logistical, methodological, and financial constraints limit local governments' capacity to conduct such studies and obtain accurate results, leading to high levels of uncertainty [29, 30]. Studies have ascribed the lack of periodic and comprehensive waste characterization studies to factors as diverse as the lack of resources, lack of capacity, low authorities' awareness, or even constraints posed by the waste collection system [30–34].

While the simplest way to conduct a HW characterization study is to sample waste in the disposal facilities from collection trucks, in many contexts this is not viable due to the waste collection system that mixes waste from different sources during collection [35–37]. In fact, in many cases the only feasible alternative is to conduct waste characterization studies directly at the source, i.e. at the household [32–37].

There is no international standard methodology for solid waste characterization [32, 34, 35, 38]. Most countries or cities design and follow their own guidelines adapted to local characteristics and reflecting the technological and financial limitations for the implementation of the studies [27, 34, 36, 39]. Thus, most industrialized countries have very specific methodologies, intended to provide highly accurate results, but require extensive resources [27, 36]. In developing countries, characterization studies are generally absent from public policy, and conducted only for major cities, with methodologies usually focusing on simplicity in the procedures and equipment rather than data reliability [3, 30, 37]. For example, in the Latin American and the Caribbean (LAC) region, most studies have used a methodology designed by the Pan American Health Organization (PAHO) in the 1980s, or an adapted version of it [37, 40–42].

Bolivia showcases many of the issues mentioned above. On one hand, it is a lower middle-income country whose major cities struggle to provide adequate MSWM services to their ever-increasing urban population [43–46]. Deficiencies in MSWM in these contexts are related to various interconnected factors such as low political priority for solid waste management issues, lack of coordination among government levels, financial constraints, and conflictive state-society relationships [47]. At the same time, the country and especially its major cities undergo a major economic transition characterized by increasing incomes and changing consumption practices [48–50], but also high prevailing inequalities [51–53]. Under these circumstances, it is crucial to obtain a good knowledge base about waste generation and its determining factors. However, there are many major gaps as the few academic studies on solid waste in the country have usually focused on sanitation and water quality [54, 55], composting projects [56, 57], and characterization of a specific stream in rural areas or towns[2] [58, 59].

The aim of this study is to conduct a waste characterization in Santa Cruz de la Sierra (Bolivia) to estimate the HWGR and composition and identify the main factors that explain the variability in these generation rates. The focus is on Santa Cruz de la Sierra (hereinafter Santa Cruz), the largest and one of the most rapidly expanding cities of Bolivia, characterized by rising incomes and high inequality [47]. The subsequent sections present: (i) the methodology; (ii) the results of the waste characterization study and the factors affecting them; (iii) a discussion of the main findings as well as some key policy implications and ways forward.

Methodology

Study site

Santa Cruz is in the eastern side of Bolivia, in an area of tropical lowlands, just around 400 m above the sea level. The climate is sub-tropical/tropical monsoon with average temperatures of 19–26 °C, average humidity of 65–81%,

[1] The term integrated sustainable solid waste management (ISWM) refers to a commonly used framework that indicates priority areas that must be considered to maintain a system that can be socially acceptable, economically viable and environmentally sound in the long term [11]. It consists of six sub-dimensions divided across two main dimensions (Technical and Governance Dimension).

[2] Cities are defined in very different ways depending on the geographical context and disciplinary lens [100]. For the purpose of this paper, we adopt the definition of "Degree of Urbanization" that divides cities across their level of urbanization [101], distinguishing three types of settlements: (a) Cities, for settlements of more than 50,000 inhabitants; (b) Towns, for settlements of at least 5,000 inhabitants and a density of 300 inhabitants per km^2; and (c) Rural areas, characterized by low population density.

and mean annual rainfall of 1251 mm ranging from 50 to 200 mm/month throughout the year [60]. Capital of Santa Cruz department[3], it is the largest and most populous city in the country. It is also the most economically prosperous, and therefore, the one with the highest MSW generation in the country (around 1800 ton/day). Historically, Santa Cruz was isolated from national development plans and remained a town (40,000 inhabitants) until the 1950s [61]. Since then, economic growth due to fossil fuels exploitation and commercial agriculture started to attract important inflows of foreign and domestic immigrants, reaching one million inhabitants in the 90 s decade, and up to 1.7 million people in 2018 [62]. Considered the centre of Bolivia's modernization and progress, the city is characterized by a strong role of the private sector, concentrating the major activities in the energy, technology, and business sectors. However, this rapid development and economic flourishment has also posed a variety of urban challenges for the city [50].

Santa Cruz had an original urban plan of concentric rings with specific land uses, based on Howard's garden city model. However, these plans were rapidly outpaced by the uncontrolled growth in the 1980s, leading to illegal settlements and deficient public service provision in the outskirts of the city [49]. Due to the geographic characteristics, and the cultural preferences of the population, the city has had a predominantly horizontal urban development [63]. While vertical housing is increasing in recent years, it is estimated that still less than 3% of the population live in apartments, being horizontal housing the widely preferred option [64]. Statistics based on collection activities estimate that HW accounts for more than 70% of the total MSW generated in the city [65].

The municipal solid waste management (MSWM) system in Santa Cruz has experienced various overlapping transitions in the last decades, influenced by factors such as population growth, urbanization patterns and state-society relations. Thus, the city is facing various challenges related to the stabilization of the collection services and disposal activities, while, at the same time, attempting to implement integrated approaches for resource recovery [47]. Most of the MSWM planning and monitoring responsibilities are undertaken by the municipal government through the municipal cleansing enterprise, which delegates the operational activities to a private company in charge of the collection and landfilling services [47]. Recycling activities are still incipient with an estimated recovery of approximately 4% of MSW, conducted almost entirely by the informal sector [44]. It is estimated that around 3000 people are involved in "waste picking" activities in the city as their main occupation. These informal wastepickers recover the recyclable material from the unsorted waste and commercialize it through middlemen or recycling industries. Although there have been attempts to achieve some level of organization in small wastepicker associations and a few networks at the local level, the working conditions and outcomes of the activity continue to be deficient [47].Similarly, composting initiatives are almost non-existent, with only a few municipal projects implemented in farmer markets [47].

Data collection

The waste characterization study was carried out in September 2018 with a total of 105 households from 3 socioeconomic strata divided across income. For each socioeconomic stratum (i.e. low-income, medium-income, and high-income), 35 households were selected and surveyed for a period of 7 days. Existing literature on waste characterization suggests that some of the most relevant aspects to consider in these studies are the proper selection of (i) sampling location, (ii) sample size, (iii) stratification and (iv) type and number of waste components [32]. The following subsections present the criteria influencing these decisions, the characterization protocol and the socio-demographic survey.

The study was conducted with the collaboration of a local university and the Municipal Cleansing Enterprise, which provided logistic support for the collection of the samples and characterization process. All study participants were provided with an extensive explanation about the research and how the results would be used. Oral consent was requested before participating in the study, while it was explained to all participants that they could decline to be part of the study at any point. The collected information was anonymised in order to protect the privacy of households and their location.

Sampling location

The sampling location is the area where the waste sample collection takes place. In contexts with a clear differentiation between the collection activities for each source (e.g., households and commerce), it is possible to collect samples directly from the waste collection trucks at transfer stations or landfills. However, this method introduces errors in relation to the estimation of the waste generation per capita, and overall provides less detailed results [32, 42].

For our study, through in-depth discussions with the municipal cleansing enterprise, and the private cleansing enterprise, it was identified that household and commercial waste in Santa Cruz is collected jointly for most areas of the city. Thus, to avoid any distortion and to obtain a good understanding of waste generation patterns, the waste sampling was conducted directly from individual households.

[3] Departments are the largest administrative division in Bolivia, followed by provinces and municipalities.

Sample size

In our study we have two types of samples, namely: (i) the sample for the determination of the waste generation rates; and (ii) the sample for the determination of the waste composition. The former reflects the number of households established to estimate waste generation rates, and the latter the number and weight of waste piles established to estimate the composition of the waste. Below we indicate the procedure adopted to determine the sizes and the sampling process for both types of samples, as there is no standardized or uniform approach in waste characterization studies for sample size determination for either waste generation rate or waste components analysis [32].

One of the methods used in developed countries establishes a minimum of 100–200 households for component analysis and 1.3% of the population for rate determination [66]. For composition analysis, the Pan American Health Organization indicates that waste characterization studies should have a minimum sampling weight of 50 kg [67, 68]. Other studies have established minimum sample sizes based on total waste sample weights, establishing that 91 kg of waste is the minimum sample for accurate and rigorous components determination [32, 69]. According to a review of waste characterization methods [32] the "ASTM recommends a sub-sample weight of 91–136 kg (200–300 lb) as recommended by Klee and Carruth (1970) [70], where one sub-sample (i.e., sample for sorting) represents one vehicle load. Sfeir et al. (1999) have investigated sorting sample weight impact on variability and reviewed the much referred to recommendations of Klee and Caruth. They conclude ''The 91 kg (200 lb) sample size commonly used may be applicable using a small number of categories (less than 10)''. Tchobanoglous et al. (1993) recommends ''common sense'' in selection of representative samples and 200 lb (91 kg) as a minimum sample size for sorting, referring to their own field studies in California and Hawaii, besides Klee and Carruth (1970)" [32, p. 1106]. Based on our interpretation of this literature, we assume that these recommendations are not limited only to waste sampling from collection trucks, but also from households.

For the waste generation rate analysis, this study uses the central limit theorem to establish the household sample size, following the similar literature [13]. Using data obtained from a characterization study conducted by the municipality in 2013 [71], our study uses a 95% confidence interval ($Z = 1.96$), a sampling error of 10% of the mean (0.058), and an estimated standard deviation of 0.75 kg/capita/day to calculate the minimal household sample size. As a result, a total of 642 observations is estimated, represented by 91 households for a period of seven days, which is the minimum number of days recommended by the literature [32]. To incorporate a security margin, a total of 105 households were included in the study to ensure the robust generation rate analysis. Subsection "Household Sample Stratification" below explains in greater detail how the study households were selected in each stratum.

For the waste component analysis, we ensured that we collected a satisfactory amount of waste from each socioeconomic stratum, which complied with the minimum weight (91 kg) recommended by the literature as discussed above [32, 69]. In this sense, the minimum waste sample collected in each stratum should have been above roughly 2.6 kg per households [i.e. 91 kg divided by the number of households in each stratum ($n = 35$)], which was achieved without problems. Given the number of strata (i.e. 3 strata), and the number of days of the study (i.e., 7 days), a total of 21 samples of waste were analysed for components determination.

Household sample stratification

The stratification process in waste characterization studies seeks to ensure that groups with different characteristics within a population are adequately included in the sample. In the case of HW characterization, various studies recommend establishing socioeconomic strata according to income levels [15, 36, 72]. Income is considered a good proxy to consumption levels and patterns [73], which directly influence the amounts and composition of generated waste [19, 74, 75].

For our study, the income levels were determined according to the geographical location and general characteristics of the households and neighbourhoods. As indicated in the Section "Study Site", the accelerated growth of the city created an urban setting where lower-income segments of the population are usually located outside the 4th and 5th rings, and medium-income households inside these borders. Upper-income households are usually located in closed condominiums and a few specific neighbourhoods across the city, most of them also inside the 5th ring.

To reflect this situation, the identification of households corresponding to each income stratum was based on a 2018 Real State Report [76], which established geographic quartiles according to housing prices: (i) Q1: 1008–1173 USD/m^2 (7016 – 8164 BOB[4]/m^2); (ii) Q2: 843–1007 USD/m^2 (5867–7009 BOB/m^2); (iii) Q3: 678–842 USD/m^2 (4719–5860 BOB/m^2); (iv) Q4: 514–677 USD/m^2 (3577–4712 BOB/m^2). For the waste characterization, it was assumed that the "High Income" strata corresponded to Q1, Q2 and Q3 corresponded to the "Medium Income" strata, and the Q4 corresponded to the "Low Income" strata. This rough classification corresponds to the general urban pattern mentioned in the previous paragraph [50, 77].

[4] The abbreviation BOB refers to Bolivian pesos.

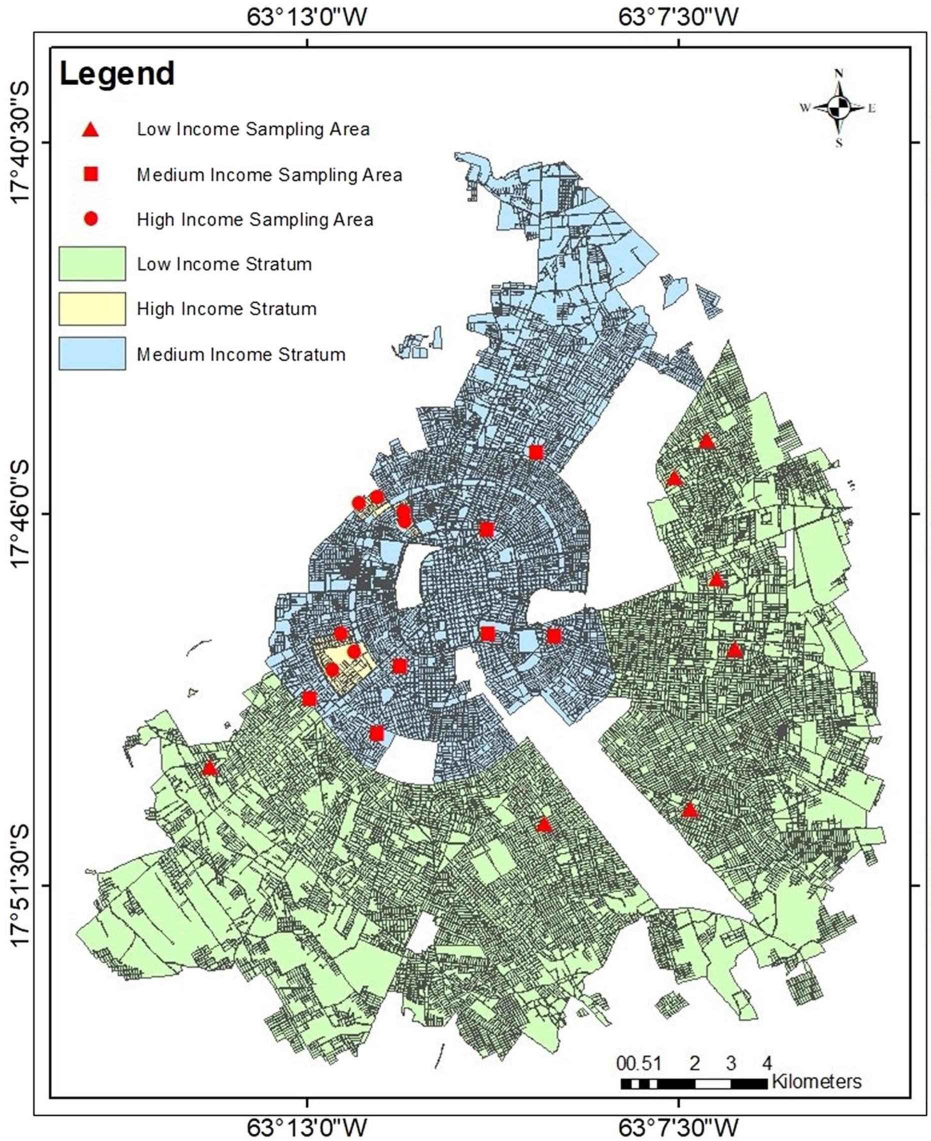

Fig. 1 Location of sampling areas across Santa Cruz de la Sierra (color figure online)

Once the areas for each stratum were delineated geographically, seven random starting points per strata were generated in ArcGIS (Fig. 1). For each random point, five households were selected following a systematic rule (See "Waste Characterization Protocol"), for a total of 35 households per stratum. In stratified sampling, such as the one used in this study, it is possible to distribute the sample size across strata using (i) equal; (ii) proportional; or (iii) Neyman's criteria. The literature indicates that if variances within strata are expected to be similar, either of the first two methods can be used [78]. Thus, the most common approach in waste characterization studies is to select approximately equal sample sizes for each stratum and then, at a later stage, calculate weighted averages based on the proportion of the strata in the population [17, 21, 32, 37]. For this study, we selected equal sub-sample sizes to assure that results obtained within each stratum have the same level of accuracy, even more when considering the relatively small size of the full sample[5].

Before sampling activities, each starting point was visited to verify neighbourhoods' characteristics according to the respective stratum. No major discrepancy was observed, so all the originally identified sampling points were maintained. Similarly, during the selection of individual households, the enumerators were instructed to perform a quick qualitative validation of the household income level on site, based on the house's general characteristics. This quick qualitative validation consisted in verifying that the selected household

[5] For example, a proportional sample size rule would have yielded an insufficient number of households to conduct the analysis for the high-income stratum (approximately 7 households), given that only 7% of the population belongs to that stratum.

(through the systematic rule) in each of the strata presented characteristics corresponding to the expected income level (Table S1, Supplementary Material). The enumerators were instructed that if this assessment had a great discrepancy with the expected income level (i.e. houses with "high income" characteristics in a "low income" neighbourhood or vice versa) they should skip that household and move to the next one. Additionally, although enumerators were also instructed to avoid selecting a property dedicated to commercial activities, this did not represent a problem considering that the sampling points were purely residential areas. Households with commercial activity were included in the study only if the specific family engaged in a minor livelihood activity (e.g., kiosk, eatery), within the same dwelling space and which was operated only by household members [18].

Type and number of waste components

The selection of waste components/categories in waste characterization studies, should balance detail and accuracy [30, 32, 36]. A larger number of waste components increases detail but decreases accuracy of results and requires more samples [39]. For the current study, a typology consisting of a total of 8 waste categories and 34 sub-categories was established prior to the start of the study (Table S2, Supplementary Material). This typology used a combination of categories from Bolivian standards and the literature review [35, 79]. These categories were included in the guidelines and training provided to the enumerators involved in the waste characterization exercise (See "Waste Characterization Protocol").

Waste characterization protocol

The overall waste characterization protocol was based on guidelines from the Pan American Health Organization (PAHO) and Bolivian standard NB-743 [68, 80] in terms of duration and calculations. However, the detailed methodology was decided following a literature review on similar studies in other countries [17, 32, 35, 79].

After household selection (See "Household Sample Stratification"), the waste characterization was conducted for a period of seven consecutive days (Figure S1, Supplementary Material). At "Day-1" the household head (HH) consent for the study was obtained and the survey was applied. Subsequently, a unique code was assigned to each household and a sticker was put on the front door for easier identification at later stages. During this day, the household members and/or other persons participating in the household waste management activities (e.g., domestic workers) were instructed to deliver the waste to the representatives of the study (who were adequately identified), instead of the municipal collection trucks during the week of the study. To facilitate this process, the samples were collected every day at the same time in the morning, before the waste collection truck passed by the neighbourhoods. Different color-coded trash bags were assigned to each stratum for easier identification during the components' separation stage. The household members were also instructed to temporarily suspend any type of recycling activities during the period of the study to avoid distorting the analysis.

During Day 0 (denominated "cleaning day"), the selected households were visited again, and their waste was collected and taken to the sorting facilities, but immediately discarded. This was done with the objective of avoiding any waste corresponding to prior days affecting the results [15, 37, 80].

From Day 1 to 7, waste from each household was collected and immediately weighted in the premises with handheld scales. Subsequently, all samples were transported to the sorting facility and grouped according to the strata. All waste was collected from the sampled households and analyzed. Components separation was done manually in a sorting table, with the weights of each category registered for the determination of their proportion for each stratum. All the recorded weights correspond to wet sample weights, as no drying procedures were applied during this step.

Waste generation rate per capita was calculated for each household for each day of the study, by dividing the total waste generated in the household during that day by the number of members reported in the survey. Subsequently, the generation rate per capita for each household was calculated using a simple average of the waste generation throughout all the days of the study. Similarly, for the composition analysis, the fraction of each waste component in the sample was calculated for each stratum for each day of the study. Subsequently, mean and median values were estimated for the generation rate and components fractions, for all strata.

Finally, the waste generation rates and composition for the whole city were estimated through weighted averages using the estimated proportion of the population belonging to each economic stratum (See "Household Sample Stratification"). To establish this proportion, due to the lack of government statistics, we used a Socio-economic Levels Study from 2017 that established that approximately 56% of the city's population fell into the low-income stratum, 37% to the medium-income stratum, and 7% to the high income-stratum [81]. The weighted average waste generation rate is estimated through Eq. 1:

$$\overline{\mathrm{Gpc}} = \sum_{i=1}^{n} \mathrm{Gpc}_i P_i \tag{1}$$

where: $\overline{\mathrm{Gpc}}$ = Weighted Average Daily Waste Generation per capita (mean or median); n = Number of strata; Gpc_i = daily Generation per capita of the strata i;

P_i = population of strata i (as percentage of the total population).

Demographic and socioeconomic survey

A survey that captured demographic and socioeconomic characteristics of the households was also conducted as part of the study. This information was used to identify the possible factors affecting the waste generation rates. The survey included basic information about (i) demographic characteristics of the household, (ii) dwelling characteristics, (iii) household expenditure, and (iv) waste generation habits.

When measuring the household size there was no age limit for members to be considered. Domestic helpers were counted in the household size only if they slept inside the sampled property. Education information was collected for all household members except for children below 3 years old and domestic helpers. However, only the household head education was considered as a variable for further analysis (See "Data Analysis"). Due to the reservations of the participants to report their income levels (See "Discussion"), we collected information that reflected the total monthly expenditure of the household services (e.g. water, electricity, phone, internet, cable tv).

Data analysis

Various statistical analysis were used to (i) identify the main characteristics of the strata (descriptive statistics), (ii) determine the statistical significance of the differences in generation rates and composition across strata (Kruskal–Wallis test); (iii) analyse the correlation between the main variables obtained through the surveys and the estimated waste generation rate (Spearman correlation analysis); and (iv) identify the main variables that could explain the variations in the HWGR (multiple linear regression analysis).

Initially, the dataset was screened to identify abnormalities such as missing data, outliers, and other sources of bias. During this procedure, the sample size was reduced to 101 households, as four households were removed for delivering the waste sample for only three days (or less) out of the seven days of study. Additionally, one daily sample of more than 6 kg per capita (~ 10 times the estimated sample average) was removed from three other households. It is suspected that these abnormal samples were caused by exceptional activities in the households (e.g., large social gatherings or periodic deep cleaning).

Subsequently, the sample distribution was explored to determine the type of appropriate statistical tests. Kurtosis, skewness, and normality tests (Kolmogorov–Smirnov, Shapiro–Wilk) were analysed to assess the sample normality. As the tests revealed that samples do not follow a completely normal distribution, non-parametrical tests were used, such as Kruskal–Wallis to establish the differences across strata; and Spearman correlation analysis to identify possible relationships between variables. Several studies similar to ours have used the Kruskal–Wallis test (or its equivalent for parametric distributions, ANOVA) to assess differences for waste generation and waste composition [28, 35, 37, 82, 83].

Finally, a multiple linear regression was conducted using SPSS software. A stepwise method was adopted including originally all the main variables that were expected to influence the generation rates based on the correlation analysis and the literature review. Through the stepwise method, the variables that did not have a significant effect were automatically removed, and only the ones found to be statistically significant and explain most of the variability in the sample were kept [84–86]. Table 1 outlines the initial set of variables and the expected effect in the dependent variable (DV) (i.e., waste generation rate).

We need to point that while regression analysis is more powerful for explaining the outcome of dependent variables, correlations can help identify whether two variables are related, the type of their relationship and its significance. In our study, the purpose of the multilinear regression analysis is to identify the most relevant factors influencing the waste generation per capita. However, the correlation analysis is used for specific purposes such as to: (i) provide more evidence of the correct stratification process; (ii) complement our discussion regarding the findings and allow comparison with other similar studies, which might have only used correlations instead of regressions. Several other studies have used similar approaches (i.e., correlation analysis and regression analysis) [1, 14, 85].

Limitations of methodology

This study was aimed at designing and implementing a robust waste characterization protocol as outlined in the previous sections, that is at the same time feasible within the context of a developing country such as Bolivia. Nevertheless, it is important to acknowledge its limitations to avoid misinterpretation of the results and identify opportunities for improvement in future research. As indicated in the previous sections, the literature has pointed four important aspects that affect the accuracy of results in waste characterization studies [32, 36], namely: (i) stratification; (ii) sample size; (iii) waste components categories; and (iv) sample location. As the latter aspect is highly dependent on the characteristics of the waste collection system in each specific case study, we will comment only on the first three aspects.

Stratification and sample size are closely linked, as the purpose of stratification is to reduce the need for larger sample sizes by dividing the study population in homogeneous subgroups [36]. Here, we followed one of the common stratification approaches for waste characterization studies [15, 36, 72],

Table 1 Variables used in the multiple linear regression

Variable	Description	Expected effect on waste generation rate	
		Direction	Reference
Waste generation rate (DV)	Average daily per capita HW generation (in kg/capita/day)	Non applicable	
Household Size	Number of family members in the household	Negative	[14, 18, 19, 23, 82, 84]
Livelihood activity	Small additional livelihood activity in the household such as an office, small kiosk, or eatery. No additional activity = 0; Additional activity = 1	Positive	[18]
Eatery	Small eatery in the household. No eatery = 0; Eatery = 1	Positive	Original. Based on [18]
Kiosk	Small kiosk in the household. No kiosk = 0; Kiosk = 1	Positive	Original. Based on [18]
Children %	Fraction of people younger than 18 years in the family	Negative/no effect	[18, 84]
HH Education	HH number of years of education	Negative/no effect	[14, 23]
Socioeconomic stratum	Low Income = 1; Medium Income = 2; High Income = 3	Positive/no effect	[18]
Cooking at home	Cooking at home as main type of meal preparation for 4 or more days a week; No = 0; Yes = 1	Positive	Original
Dwelling ownership	Type of ownership level of dwelling. Borrowed = 1; Rented = 2; Leased = 3; Owned = 4	Positive/no effect	[87]
Service expenditure	Monthly per capita expenditure of all household services such as water, sanitation, electricity, phone, internet, cable TV (in BOB/capita)	Positive	Original. Based on [13]
Garden waste recovery	Separation and recovery of garden waste for composting. No recovery = 0; Recovery = 1	Negative	Original
Food waste recovery	Separation and recovery of garden waste for composting or animal feeding. No recovery = 0; Recovery = 1	Negative	Original
Waste separation	Source separation of recyclable waste to donate, compost, crafts, or other purposes. No separation = 0; Separation = 1	Negative	Original

which divides the population in three or more strata, according to their income. One limitation lies in the criteria used for the stratification, due to the lack of publicly available statistical information at the municipal level in Bolivia. In this regard, we used real estate reports to broadly identify the geographical areas of the city where the households of each income strata are located (See "Household Sample Stratification"). Conversely, we used a consultancy report from a market research private organisation to identify the percentage of the population belonging to high-, middle- and low-income groups to estimate the generation rates at the city level (See "Waste Characterization Protocol"). Thus, it is possible that the income groups of the two sources do not perfectly correspond with each other, affecting to some degree the results obtained for each stratum and consequently the estimates at the city level. While lack of public statistical information is a common feature in developing countries, the existent literature suggests that even within the Latin America context, the case of Bolivia is particularly difficult, as studies in other countries of the region have cited public databases for the stratification process [17, 37, 88]. Furthermore, other studies, in contexts with availability of detailed public statistical information, have established more strata or used other variables for strata definition [15, 19]. This could also contribute to the improvement of accuracy in the estimates.

Results

Household survey

The main socio-demographic characteristics of the sample are described in Table S3 (Supplementary Material). Variables such as gender, role, age, and education refer to the respondent, while size, and service expenditure per capita refer to the whole household.

Figure 2 displays the prevalence across strata of some solid waste practices that could affect the overall waste generation. Approximately 86% of the households indicate that the main food consumption practice is cooking at home at least 4 days a week, with this preference distributed proportionally across strata. Additionally, 14% of the households indicate that they carry out an additional livelihood activity at home such a small eatery or kiosk, with a higher prevalence in the medium-income strata. Additionally, 33% of the households separate their waste, mostly in the high-income strata. Only respondents from low-income strata engage in waste burning.

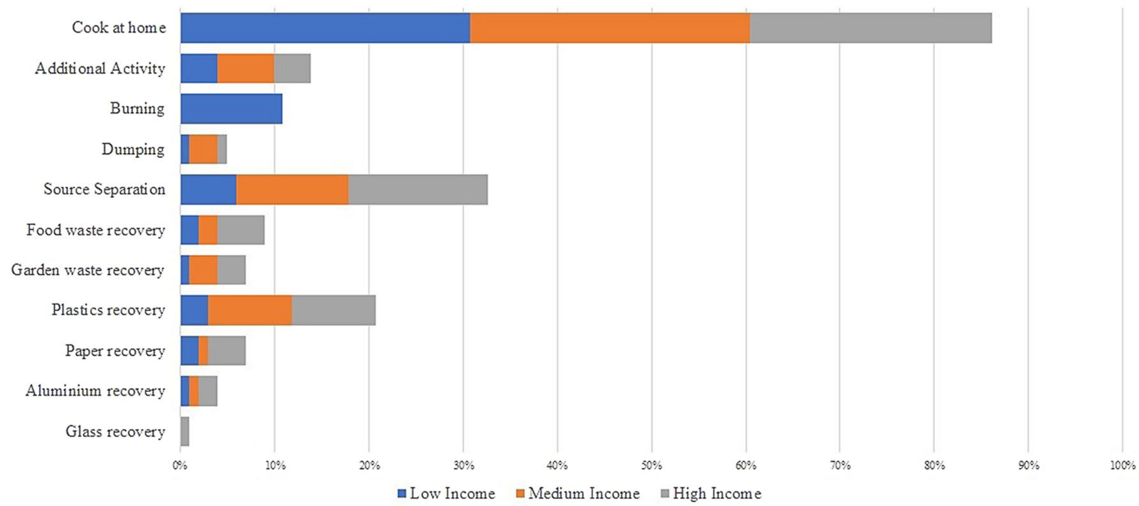

Fig. 2 Prevalence of solid waste management practices across socioeconomic strata (color figure online)

Table 2 Waste generation rates

Measure	Pooled sample (kg/cap/day)	Low income (kg/cap/day)	Medium income (kg/cap/day)	High income (kg/cap/day)	Weighted average at city level (kg/cap/day)
Mean	0.745	0.608	0.856	0.771	0.711 (~1225 ton/day)
Median	0.581	0.513	0.588	0.618	0.548 (~943 ton/day)
Std. deviation	0.528	0.376	0.648	0.510	–
Minimum	0.113	0.112	0.186	0.248	–
Maximum	2.631	1.834	2.631	2.210	–
Skewness	1.573	1.563	1.393	1.275	–
Kurtosis	2.124	2.902	1.150	0.819	–

Household waste characterization

Household waste generation rates

Table 2 contains the HWGR per capita for all socioeconomic strata. Values of skewness and kurtosis, as well as histograms (Figure S2, Supplementary Material) for the full sample and each stratum depict a right skewed distribution. As showed in Table 2, median HWGR consistently increases from the low income stratum (0.51 kg/capita/day) to the medium stratum (0.59 kg/capita/day, and the high (0.62 kg/capita/day). For mean values, HWGR rate is the lowest for the low-income stratum (0.61 kg/capita/day) and the highest for the medium-income stratum (0.86 kg/capita/day). HWGR for the highest income stratum reaches 0.77 kg/capita/day. The Kruskal–Wallis test was conducted for the median values across strata, resulting in a p value of 0.373, which indicates non-statistically significant differences across the three strata.

The waste generation for the entire city is estimated through a weighted average using the estimated proportion of people in each socioeconomic stratus (See "Waste Characterization Protocol"; "Data Analysis"). Overall, it is estimated that median waste generation is approximately 0.548 kg/capita/day. With an approximate of 1,722,480 inhabitants in 2020, the estimated median waste generation for the entire city is 943 tons of HW per day. Similarly, the mean waste generation is calculated to be around 0.711 kg/capita/day, resulting in a mean generation of 1225 tons/day for the entire city.

Waste composition

Table 3 outlines the fraction by weight of each waste component calculated daily across strata with Figure S3 (Supplementary Material) illustrating more clearly the median values across strata for each component. The Kruskal Wallis test shows that differences in the fractions of organic, plastics, glass, sanitary waste, and fine residue are statistically significant between socioeconomic strata. The organic waste component is significantly higher in high- and medium-income households, while the highest fraction of fine residue

Table 3 Waste components across income strata

Component	Low		Medium		High		Estimation at city level (%)
	Mean (%)	Median (%)	Mean (%)	Median (%)	Mean (%)	Median (%)	
Organic**	55	57	68	69	68	70	63
Plastics**	9	9	7	6	8	7	8
Paper	2	2	3	2	4	3	2
Metals	1	1	1	1	2	1	1
Glass	0	0	1	2	3	2	1
Fine residue**	15	15	7	5	2	2	10
Sanitary waste **	11	11	6	5	8	8	9
Others	7	5	7	7	5	6	6

**$p < 0.05$

is in low-income households. Similarly, the sanitary waste was relatively higher in low-income households in comparison to high- and medium-income strata, while plastics fractions were very similar across strata. The estimation of the fractions at the city level was calculated through a weighted average of the median fractions of each component for each stratum and their estimated population.

Factors affecting waste generation

Table 4 displays the Spearman correlation analysis for the key variables collected through the household surveys and the generation rate per capita estimated for each household (See "Household Generation Rates"). Results back up the stratification process conducted, showing strong and significant positive correlations between the strata (low-, medium-, and high-income) and the service expenditure per capita (0.585, $p < 0.01$), as well as the education of the HH (0.603, $p < 0.01$) (Table 4). Moderate negative correlations were found with the household size (− 0.292, $p < 0.01$) and percentage of children (− 0.369, $p < 0.01$), reflecting the expected demographic characteristics according to income level.

The generation rate per capita, was found to have a strong and significant negative correlation with the household size (− 0.622, $p < 0.01$), moderate negative correlation with the percentage of children (− 0.328, $p < 0.01$) and weak positive and negative correlations with the service expenditure per capita (0.212, $p < 0.05$) and the recovery of garden waste (− 0.214, $p < 0.05$), respectively (Table 4).These findings reflect expected connections between the variables and generation rates according to existent literature (Table 1). For instance, household size and proportion of children are directly linked to socio-economic levels, which suggests that the overall influence mechanism could be related to consumption habits. Another possible explanation relates to smaller levels of consumption in children compared to adults. Regarding the household size, it is possible that a larger household size leads to a more efficient use of food and other inputs for intra-household activities.

Subsequently, a multiple linear regression was employed to identify the variables that have the highest influence on HWGR per capita (Table 5). As mentioned in the "Data Analysis" subsection, a stepwise procedure was used for the regression analysis to assure that the selected models contain only the variables that are statistically significant and that explain most of the variability in the dependent variable. Possible multicollinearity was discarded by running collinearity diagnostics for each of the independent variables and verifying that the Variance Inflation Factor (VIF) in all cases was below 4 [1].

In total, 4 models were identified by the statistical software as the most suitable (Table 5). Model 4 explains most of the variability, with an adjusted R^2 value of 0.342. Standardized coefficients show that the largest effect in the HWGR originates from the household size and the fraction of children, followed by the HH education and the existence of a small kiosk in the household.

Discussion

Household waste generation rates and composition

The HW generation rate estimated in this study (0.711 kg/capita/day) is comparable to the outcomes of similar studies in the most urbanized cities of Bolivia [71, 89] and the LAC region. For instance, studies from Mexican cities of similar size to Santa Cruz conducted in the early 2000s reported HWGR between 0.51 and 0.98 kg/capita/day [15, 17, 21, 88]. Studies from the early 2010s in other more industrialized cities of Latin America such as Sao Paulo and Buenos Aires reported higher HWGR at 1.0 kg/capita/day and 1.1 kg/capita/day respectively [90]. Similarly, in terms of waste composition, our study estimates a predominance of the organic fraction (63%), slightly above the reported values

Table 4 Correlation analysis for selected variables

Variable	Strata	Household Size	Children (%)	Dwelling ownership	Eatery	Serv. expend. capita	Source separation	Food waste recov	Garden waste recov	HH education	Waste generation rate
Strata	1.000										
Household size	− 0.292**	1.000									
Children %	− 0.369**	0.483**	1.000								
Dwelling ownership	0.130	0.080	− 0.201*	1.000							
Eatery	0.003	0.137	− 0.042	− 0.131	1.000						
Serv. expend. capita	0.585**	− 0.511**	− 0.447**	0.219*	− 0.060	1.000					
Source separation	0.242*	0.010	− 0.083	0.065	0.053	0.058	1.000				
Food waste recov	0.131	− 0.015	0.139	− 0.160	0.205*	0.027	0.449**	1.000			
Garden waste recov	0.099	0.168	0.026	0.118	− 0.039	− 0.013	0.392**	0.051	1.000		
HH education	0.603**	0.011	− 0.174	0.286**	− 0.133	0.445**	0.165	− 0.012	0.046	1.000	
Waste generation rate	0.117	− 0.622**	− 0.328**	− 0.084	− 0.010	0.212*	− 0.113	− 0.103	− 0.214*	− 0.166	1.000

*$p < 0.05$

**$p < 0.01$

Table 5 Models coefficients and fit statistics

Model	Variables	R	R^2	Adjusted R^2	Unstd. coeff	Std. Error	Std. coeff. beta	Sig
1	(Constant)	0.515	0.266	0.258	1.309	0.107		0.000
	Household size				− 0.112	0.019	− 0.515	0.000
2	(Constant)	0.550	0.302	0.288	1.597	0.166		0.000
	Household size				− 0.113	0.019	− 0.520	0.000
	HH education				− 0.023	0.010	− 0.192	0.027
3	(Constant)	0.578	0.334	0.313	1.667	0.166		0.000
	Household size				− 0.093	0.020	− 0.431	0.000
	HH education				− 0.027	0.010	− 0.223	0.011
	Children %				− 0.005	0.002	− 0.202	0.037
4	(Constant)	0.608	0.369	0.342	1.627	0.164		0.000
	Household size				− 0.091	0.020	− 0.420	0.000
	HH education				− 0.026	0.010	− 0.214	0.012
	Children %				− 0.006	0.002	− 0.227	0.017
	Kiosk				0.341	0.150	0.189	0.026

from the LAC region (48–57%) [15, 17, 21, 88, 89], but in line with studies in developing cities of Africa and Asia (above 60% of organic fraction) [91–93]. Another particularity is the high level of fine residue, which reaches values of above 10% for the whole city, and up to 15% for the low-income stratum. While some studies do not report this waste category separately, the ones who do it report fractions around 5% [17, 88, 89]. However, when looking at studies in less developed cities or more rural areas, the fraction of fine residue is similar to those found in our study [3, 72].

Factors influencing waste generation rates

Income and urbanization[6] have been identified as two major drivers of increasing HWGR across multiple countries [12]. Although many studies have attempted to establish these effects at the household level, only few have successfully managed to make these connections (See "Introduction") [13, 23]. Our study finds a positive and statistically significant correlation between HWGR and expenditure per capita (Table 4), and a difference in median HWGR across strata (Table 2) suggesting higher HWGR in higher income households. However, these differences are not statistically significant, while the relevant variable was discarded during the multiple linear regression analysis, as it failed to contribute significantly to the explanation of the DV (See "Factors affecting Waste Generation").

This could be explained by the fact that household consumption habits might not necessarily depend predominantly on income. Rather they could be influenced more by cultural and social factors such as cooking practices, dwelling characteristics, or transportation patterns [15, 85, 87, 94], which could be in turn influenced by income depending on the context [72, 87]. In our study, we tested a variable related to cooking practices (See Table 1) but were unsuccessful in establishing a connection with generation rates (See Section "Factors affecting waste generation". Other studies have suggested that income differences might be more visible in the waste generation rates of other economic sectors such as the commercial, food and leisure, with urban residents engaging more in consumption activities outside the household [83, 95].

At this part it should be noted that ideally both income and expenditure should be tested as possible factors influencing waste generation rates. However, capturing accurate and reliable income information is often challenging [72], which is why similar studies have used varied proxies such as rental rates [13], expenditure [72, 96], location [72], dwelling size [91], or property taxes [19] for the stratification process and/or the statistical analysis. In this study while we generally recognize that income can potentially affect waste generation, the influencing mechanisms are still unclear, with very

[6] Urbanization dynamics are closely linked to households' lifestyles and dwelling characteristics, which, in turn, influence waste generation and waste management activities. These dynamics have informed the design and implementation of our study in multiple ways. First, the location of each income stratum area is directly linked to the urbanization pattern of the city (see section "Household Sample Stratification"), while some of the factors validated by enumerators on site during household selection (e.g. road pavement, stray animal prevalence) related to neighbourhood characteristics and are directly influenced by urbanization patterns (See Table S1, Supplementary Material). Second, urbanization dynamics influence household size [102, 103] and cooking habits [104–106], which we use as a variables in this study (Table 1), although the effect of the latter was not demonstrated through the analysis. Third, urbanization dynamics influence dwelling characteristics [107, 108]. In Santa Cruz de la Sierra the predominantly horizontal development and prevalence of domestic gardens conduced us to expect that they would affect the amount of organic waste generation. Thus, we used "garden waste recovery" as a variable (Table 1), although its effect was not demonstrated through the analysis.

different findings between studies [97, 98]. Furthermore, it is also currently unclear in the literature whether income is a better predictor than expenditure. For instance, a study from Vietnam that tested both income and expenditure per capita found that expenditure was actually a more influential predictor of waste generation in residential areas [96], while a study in Cambodia [72] found neither of the two variables to have a statistically significant relationship with household waste generation.

Various studies have found household size to influence negatively HWGR [3, 18, 23, 83, 85]. However, to the best of our knowledge, Lebersorger and Beigl [85] is the only study that has reported the standardized coefficient, representing the strength of the influence (− 0.328 in their study). This estimate reflects well the coefficient estimated in our study (− 0.42) (Table 4).

Regarding education, this study identified statistically significant negative effects of higher levels of education on HWGR with estimates similar to a study conducted in the city of Mexicali [23]. In their model (controlling for income), education appeared to have a negative effect in waste generation. While our regression analysis does not include income, the effect of education is also negative, with a standardized coefficient value of − 0.214.

Finally, the existence of an additional activity such a kiosk, influenced positively HWGR [18]. In this study, we tested this variable in two ways, one considering all types of businesses, and one by separating the types of businesses as different variables. Results suggest that considering only kiosks as the variable of interest, the effect on HWGR is positive, representing an increase of HWGR by 0.189 standard deviation units compared to households that do not have a kiosk as additional business.

The urban characteristics seem to exert some influence on HWGR rates and composition. The correlation and multilinear regression analysis suggests that as family sizes decrease and people move to vertical housing due to changes in demographic and urbanization patterns, HWGR will increase (Table 5), and organic fractions will decrease due to changes in household's garden space and consequently, garden waste will decrease as well (Table 4, Section "Household Waste Generation Rates and Composition"). This has been identified in other developed and developing parts of the world, especially those that are rapidly urbanizing [35, 85]. However, the speed of these changes might depend greatly on urban planning policies that generate these changes at the household level.

The complex interaction of factors influencing waste generation rates and composition will continue to bring changes in these variables in Santa Cruz, as the city continues its urbanization process. If both MSWM officials and other officials in the municipal government are aware of these interactions, these changes can be predicted to some extent and adequate measures put in place [25, 26]. For instance, a characterization study in Cambodia has drawn insights related to the demand for collection vehicles and the feasibility of composting activities in unserved communities [72]. Elsewhere, Dyson and Chang studies have relied on characterization data to select the best location for material recover facilities using systems dynamics modelling [26]. Waste composition data has also been used to reflect on the effects of various features of urbanization and discuss the appropriate criteria to determine waste disposal fees [99]. These are important avenues for research that should be considered in Santa Cruz, given its rapid urbanization process and the deficiencies in their current MSWM system [47].

Finally, when considering the limitations of this study (see "Limitations of methodology") future research in Santa Cruz de la Sierra should seek to undertake waste characterization studies during different periods of the year, in order to investigate the possibility of seasonal variations in the waste generation rates and composition, and further validate our findings about the possible influencing factors. For instance, studies in the United States have suggested that in some areas up to 6 characterization studies per year could be necessary [39]. Seasonality in waste generation could relate to very diverse factors including changes in weather conditions (e.g., more leaf waste during the windy season) or periods with atypical levels of consumption (e.g., Carnival, Christmas, New Year) [66, 73, 88, 91, 93]. Findings from such robust studies could be integrated in meta-analyses to identify waste generation patterns both within Bolivia, but more broadly other rapidly urbanizing contexts of Latin America and other developing regions.

Conclusion

This study estimated waste generation and composition at the household level, as well as the main factors explaining variability in Santa Cruz, a rapidly urbanizing city of Bolivia. To achieve this, we surveyed 105 households from three socioeconomic strata. We collected over a period of seven days the entirety of generated waste, which was weighted on site, transported to a facility and grouped by socioeconomic stratum, to conduct the components sorting and identification.

The HGWR across income strata and estimations at the city level show results comparable to other cities in Bolivia and other developing countries. The waste composition analysis finds the large presence of organic material and fine residue, at levels that are closer to less developed cities. These results suggest urban living and consumption patterns that are the combined outcomes of the rapid economic growth and urbanization found in large cities on the one hand, with the cultural preferences and habits of smaller town on the other hand. There is some evidence about the influence of income levels on HWGR through correlation analysis. However, through the regression analysis, the main factors explaining the variability in HWGR are the household size, household education, percentage of children in the household and the operation of a kiosk by the household. These factors and their short-, medium-, and long-term dynamics should be adequately considered for the effective municipal solid waste management planning in the city.

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