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Solid Waste Characterization and Management in a Highly Vulnerable Tropical City

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Abstract: Inadequate waste management can cause human health problems, economic losses, and environmental contamination. Colombian municipalities face the critical issues of very low levels of recycling for solid waste, increasing waste quantities, precarious conditions for waste pickers, a lack of investment in alternative strategies, increasing pollution, and landslides in landfills. Moreover, Colombia lacks an in-situ quantification of solid waste, as well as alternative strategies based on an analysis of the local contexts. This study provides an analysis of the current waste management and a characterization of the waste production in a highly vulnerable tropical city in Colombia, Puerto Carreño, the capital municipality in Vichada. Systematically following the collection routes, we determined that 61% of waste produced is potentially recyclable, and that the total solid waste per inhabitant (at 0.504 kg/capita/day) is 43% lower than that estimated by the private local waste collector. The great majority of solid waste is disposed of in El Merey landfill, which does not currently fulfill legal requirements. Given the current incentivization legislation, formal economic gains can be achieved, including an increase in employment, and the reduction of negative social and environmental impacts near the landfill, and it is estimated that its useful lifetime can be doubled (+30 years) within a circular economy framework. This study is an important contribution for local and national authorities to implement key waste-management recommendations, including the formalization of indigenous waste pickers, implementation of selective collection routes, agricultural exploitation of the organic waste, and adequate landfill management.

Keywords: characterization; solid waste; integrated management; indigenous community; waste pickers; tropical city

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1. Introduction

Solid waste comprises materials that are discarded after their useful life, and that in general have no economic value in themselves. The discarded objects can come from industrial, commercial, mining, agricultural, and general day-to-day activities [1]. The World Bank report entitled "What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050" [2] indicated that, owing to accelerated urbanization and population growth, if no urgent action is taken, global solid waste will increase by 70% by 2050, rising from 2010 million tons of waste in 2016 to 3400 million tons in 2050.

The report [2] also indicated that 36.7% of the world's solid waste is disposed of in landfills, and 33% goes to open dumps, leaving a small proportion for other final disposal mechanisms, such as incineration, composting, and recycling, where it is estimated that only 13.5% of the waste is reincorporated into new productive goods or services.

The proportion of solid waste recycled in Colombia, ~11.1% according to the Colombian National Administrative Department of Statistics (DANE) [3], places it in the bottom three of OECD countries [4]. However, this percentage does not account for territories where no data are available; in several regions, recycling activities are not carried out [5] because of a lack of resources and tools to enable transformation of the waste into raw

materials for goods or services [6]. Vichada, the region of this study, is one such Colombian region, where the recycling rate may be much lower than the national average [7].

In Colombia, recycling is considered a legal economic activity led by professional recyclers [8]. In total, 54 of Colombia's 213 municipalities with more than 5000 users have waste pickers, which means that only 21% of the country has inclusive and formal recycling [9], while the remaining regions are not complying with this obligation [7].

According to the national report on the final disposal of solid waste [10], within the regulatory framework for domiciliary public services, the largest portion of Colombia's waste, around 56%, is finally disposed of in authorized landfills, with another 5% in contingency cells. The authorized landfills are required to have an environmental license issued by a competent environmental authority [11]. Open-air landfills, which are not authorized by Colombian regulations, account for 33% of final waste disposal, and unauthorized temporary cells account for 5% [10].

Consequently, only 61% of the national territory has an authorized final disposal solution and even that solution has shortcomings that reduce its effectiveness [12] and generate various social and environmental effects [13]. Landfills generate major impacts for the communities living around them in particular such as the environmental impacts due to soil contamination, generation of greenhouse gases produced by the decomposition of garbage, generation of unhealthy conditions such as an increase in rodents, mosquitoes, and associated diseases [12], and landfill disposal becomes more inefficient in economic terms and more negative socially and environmentally [14] when it is not combined with other disposal techniques, such as recycling.

In response to these issues, Colombia has developed a national circular economy strategy, which includes, as one of its compliance indicators, the waste recycling rate, specified in the Consejo Nacional de Política Económica y Social (CONPES), document 3874 [15] to encourage the use of waste as a raw material. However, this initiative depends on the separation of waste at its source of production and the mechanisms for transporting waste types separately according to their classification.

Thus, to provide a diagnostic and solution that can be easily implemented in tropical areas of Colombia and the world, and to promote the transition of Colombia's small cities from waste management based on a linear economic system to one based on the circular economy [16], this study aimed to answer the following questions:

(i). How much and what solid waste is generated in the vulnerable tropical city, Puerto Carreño?
(ii). What are the key waste-management issues?
(iii). What are the realistic waste-management recommendations considering the local context?

2. Methodology

2.1. Study Area

Puerto Carreño is the capital municipality of the department of Vichada, Colombia, located in the Eastern plains (llanos), near the Venezuelan border (Figure 1), and with an estimated population of 15,697 persons in 2020 [17]. Currently, urban waste is sent to a landfill called "El Merey", which, according to data from the residential public service provider [18], has a cell for the burial of non-recyclable solid waste (Figure 1D). It is completely uncovered and does not comply with the operating criteria of the Colombian regulations, which establish that daily coverage of waste must be guaranteed [8].

The weighing and registration of each of the vehicles entering the landfill are not guaranteed [19], generating discrepancies in terms of the actual waste produced in the population [18], which makes an accurate estimation of the composition of the waste and its potential for use impossible. The recycling activity is mostly carried out by the indigenous population, who lives in areas surrounding the landfill and enter it to separate recyclable waste, such as plastic, metal, paper, and cardboard, among others, for commercialization purposes (Figure 1A–D).

Considering that the solid waste disposed of in the landfill should only be waste that cannot be used due to its physical and chemical conditions [10], it is evident that the municipality does not have selective collection routes, which effectively contribute to the separation of waste at the source and thus avoid the disposal of recyclable waste in the landfill.

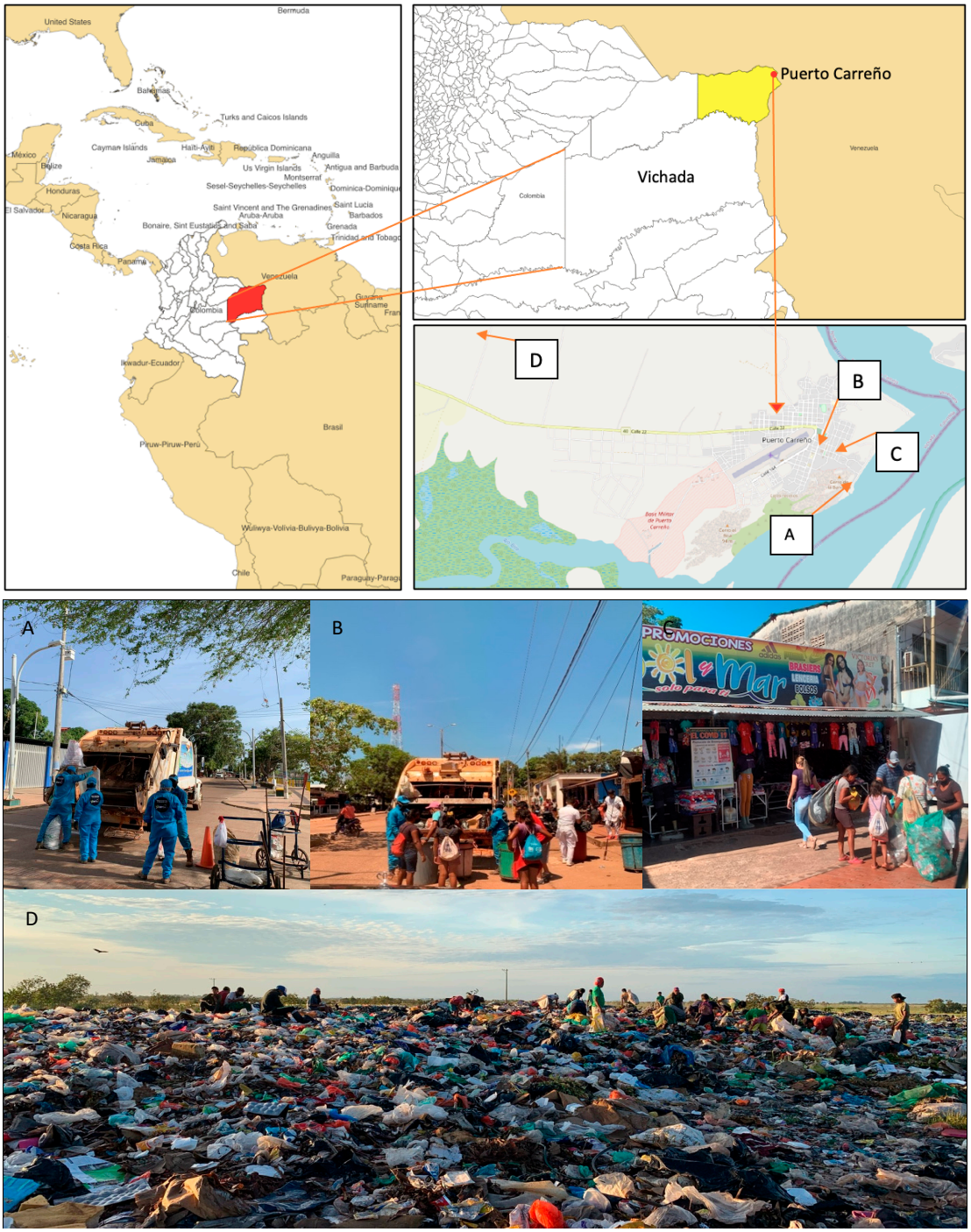

Figure 1. Map indicating the location of the Department of Vichada, shown by the red and yellow areas; the orange dot indicates the capital municipality of Puerto Carreño and the places where the photos were taken. Waste collection and transportation process in a residential area (Image **A**); intervention by the recycling indigenous community (adults and children) in the waste-collection route in a commercial area (Images **B** and **C**), and the indigenous community separating recycling materials from the solid waste in the solid waste-storage cell of the El Merey landfill (Image **D**).

2.2. Current Situation in Puerto Carreño, Vichada, Colombia

In response to various demographic conditions in the municipality, the indigenous population has migrated to the capital municipality to separate solid waste for commercialization, which is their main source of income (Figure 1B,C).

Although there is no formal census to establish the ethnic groups of the communities engaged in informal recycling activities in the municipality, various sources [20,21] report the presence of the Amorúa, Sikuani, or Jivi indigenous communities, which are the closest indigenous communities to the municipal capital. There are also reports of non-indigenous people, who may be of Colombian or Venezuelan origin, engaged in informal recycling. Vichada is among the most vulnerable departments of Colombia, where 68% of the population has unsatisfied basic needs [22].

Various national media sources have reported on the current social problems experienced by this population of informal recyclers, who are suffering from malnutrition [23], among other affectations, because they consume garbage as food, as their only means of survival (Figure 1D). The highly vulnerable situation of the indigenous waste pickers in Puerto Carreño has been internationally condemned for more than a decade, but with no substantial improvement so far [24].

Only 21% of Colombia's municipalities with more than 5000 inhabitants have adequate recycling [7], which means that 79% of the municipalities carry out this activity without minimum decent conditions or do not recycle at all. Similarly, of the 1123 municipalities in Colombia, 140 municipalities have an index of unsatisfied basic needs equal to or greater than that of Puerto Carreño (41.98%), i.e., 12.46% of the Colombian territory has similar social and economic situations to those of the municipality of Puerto Carreño [22].

Moreover, 9 out of 10 municipalities have a recycling rate lower than 12.9% while 3 out of 4 with a recycling rate lower than 3%. Puerto Carreño is one of those latter municipalities [10], with similar recycling rates in Latin America and the Caribbean in general (i.e., 4.3% [2], with even lower rates in the Caribbean).

2.3. Characterization of Solid Waste

The main objective of solid waste characterization is to understand the composition of waste generated by a population group, such as a neighborhood, a city, or a country [25].

Although there are different methodologies to identify the composition of solid waste, there is agreement that the task is not easy because there are different sources of waste generation and different means of waste disposal, among other challenges [26].

This characterization of solid waste is based on the Technical Regulation for the Drinking Water and Basic Sanitation Sector, known as RAS [27], which establishes that to determine the generation of waste at the place of origin, a measurement of the waste presented by the users or generators of the waste must be made, taking into account the socioeconomic stratum and the type of generation (i.e., differentiating between commercial and domestic generation).

In terms of the socioeconomic stratum, the municipality of Puerto Carreño consists of low and middle socioeconomic strata, as they are commonly known in Colombia, which means that the economic conditions of the population do not vary significantly and hence there is no significant difference in terms of solid waste production across neighborhoods.

In terms of differentiation by type of generation, one of the six waste-collection routes focuses on the central sector of the municipality (Route E), which is mainly commercial, whereas the other routes are mainly residential. Therefore, the present characterization distinguishes the waste production of this route from the other five routes. The residential waste collection routes are operated on two different schedules, twice a week: waste from routes E, F, and B is collected in the morning and that from routes A, C, and D in the afternoon.

Industrial solid waste was not considered in the characterization because according to Colombian regulations [8], large generators of solid waste, such as industries, must carry out the integral management of their waste separately and therefore, they can privately contract the waste collection and transportation company and must pay different rates.

The final disposal of waste in Colombia operates under the door-to-door collection model [28], where the solid waste collection vehicle makes a trip to collect the waste, and the users leave the waste for collection on the sidewalk, usually in front of their homes. This model is widely used because most Colombian rural regions [29] do not have large-volume containers for waste disposal nor automated vehicles for automatic collection [30].

The nature of the collection model is important because users leave their waste on the public roads for collection, meaning it is exposed to environmental conditions but it also enables the indigenous community to separate the waste on the street, rather than at the landfill, and then take away the recyclable waste to sell it.

This characterization of the waste started in February 2021 in parallel with the start of the waste collection to avoid changes in the estimation of waste in terms of weight and quantity between the user disposing of it and collection by the solid waste-collection vehicle. This is essential to avoid the exposure of the waste to environmental conditions for long periods and to enable accurate estimation by avoiding separation of waste by the recycling community. In terms of the number of samples, based on the methodology proposed by ref. [31] and applied by ref. [26], and given that the municipality has six collection routes, 25 samples were taken (i.e., bags of solid waste) for each of the micro-routes that were delivered by users for final disposal. The samples weighed a total of 389.47 kg when combined.

The following three main classifications, which correspond to the Colombian regulations on solid waste [32], encompass nine sub-categories: (1) recyclable organic waste, (2) recyclable inorganic waste, and (3) non-recyclable waste.

Following ref. [33], the first classification refers to (i) food waste and (ii) organic waste such as vegetable waste product of the pruning and cutting of trees and plants, the second classification refers to (iii) plastics, (iv) paper, (v) cardboard, (vi) glass, (vii) metals, (viii) textiles and the third classification refers to (ix) other non-recyclable waste such as sanitary waste, sweeping waste, and other general materials that are not marketable in Colombia.

2.4. Estimated Solid Waste Production

To estimate the useful lifetime of the "*El Merey*" sanitary landfill, the percentage distributions of waste were used, obtained from the characterization, and the population estimates of the DANE [17] to determine the average production of recyclable and non-recyclable waste until the year 2035.

Similarly, and following the methodology of the RAS, which recommends the use of any technically valid method [27], the following DANE methodological indicators were used [34]:

$$SWP_{jt} = \frac{TSW_{jt}}{TP_{jt}}$$

where SWP is the tons of solid waste generated per capita, TSW is the total tons of solid waste generated, and TP is the total population of the study area, and all variables refer to the reference spatial unit j, and the corresponding time t.

In Section 3.2 below, where the production of waste per person per day was calculated, it was considered that (i) the total waste is reported monthly by the collection and transport company, and second, (ii) this estimation of the waste collected per route during the characterization is based on the technical characteristics of the collection vehicle, as well as the average volumetric density of the different types of solid waste. It is important to point out that this independent estimation (i.e., part (ii)) is required because there is currently no weighing machine at the landfill [19]. Therefore, although the reports are

official, the weights are "visually estimated" by the waste-collection company, and thus crucially lack accuracy.

3. Results and Discussion

3.1. Characterization of Solid Waste

The results obtained according to the classification and subsequent weighing are shown in Figure 2 and Supplementary Table S1. This procedure was carried out for each collection route to determine if there was a significant difference in waste production between routes.

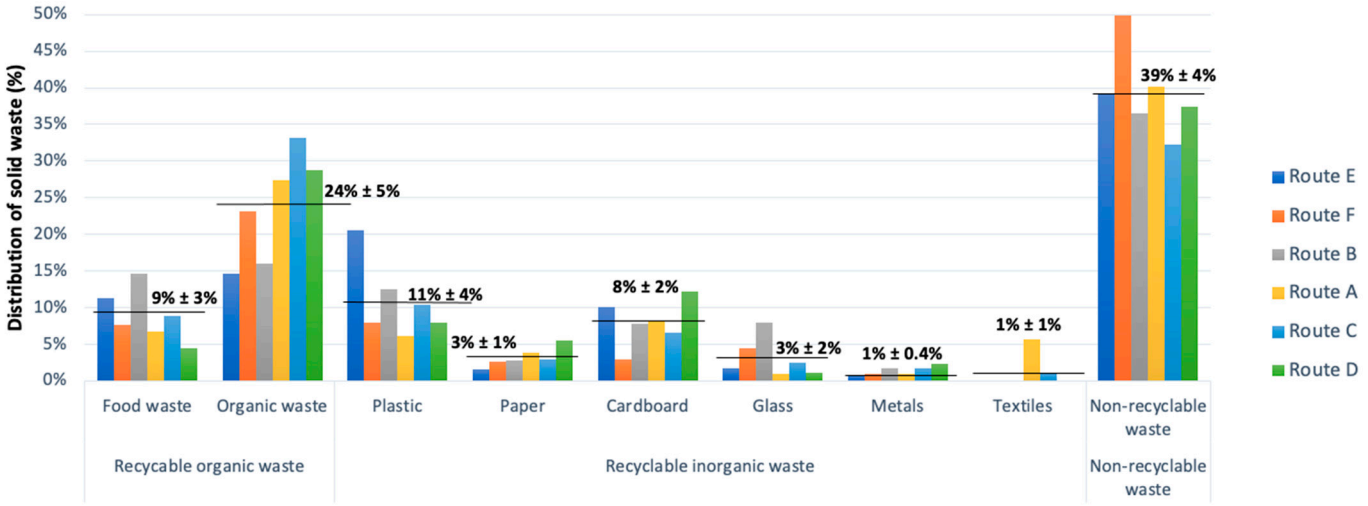

Figure 2. Percentages of solid waste produced by types of waste for the six collection and transportation routes (colored bars) in the municipality of Puerto Carreño. Each black horizontal bar represents the weighted average of each category with a 95% confidence interval for Puerto Carreño.

From these results, adding up each of the materials, the production of waste by types of waste for the city of Puerto Carreño was obtained and is shown in Supplementary Tables S1 and S2.

Across the six collection routes, in this study, it was found that 61% (±4%) of the solid waste produced in Puerto Carreño is recyclable (the sum of recyclable organic waste and recyclable inorganic waste, see Figure 2). In particular, recyclable waste is composed of the following waste materials, in decreasing order: organic waste, 24% (±5%), plastic, 11% (±4%), food waste, 9% (±3%), cardboard, 8% (±2%), paper and glass, approximately 3% (±1%), and metals or textiles, approx. 1%. In total, 39% of the waste, including materials such as sweeping debris, sanitary waste, and disposable food packaging, is non-recyclable.

Thus, given this estimate that 61 (±4%) of the waste produced in the municipality is recyclable, based on the 2020 solid waste production of 5085 tons (reported by the company in charge of waste collection in Puerto Carreño), approximately 3101.8 tons of waste should be recycled rather than go to the El Merey landfill.

3.2. Estimated Solid Waste Production

To estimate solid waste production, the per capita production of solid waste for the year 2020 was first calculated based on the reports by the company (EMPCA, pers.comm.) in charge of waste collection (5085 tons/year for a population of 15,697 inhabitants in 2020):

$$SWP_{company} = 0.887 kg/capita/day$$

Next, the per capita production of solid waste for 2020 by was estimated calculating the weight of the solid waste that the collection vehicle can transport, given that it makes two daily collections from Monday to Saturday (the service is not provided on Sundays) (see Supplementary Table S3). On this basis, the municipality produces 4.62 tons of recyclable

waste per collection for each transportation route, which corresponds to an average of 9.24 tons per day and 55.44 tons per week.

Thus, for the 313 collection days of the year, there is a solid waste production of 2892 tons/year, which gives us the following per capita production of solid waste:

$$SWP_{ourstudy} = 0.504 kg/capita/day$$

This figure ($SWP_{ourstudy}$) is 43.1% lower than the estimate based on the data provided by the waste collection company ($SWP_{company}$).

Using this value and considering population projections up to the year 2035, the yearly production of solid waste (2020–2035) that could be recycled during this time was estimated. As shown in Supplementary Table S4, if 61% of the waste generated in the municipality is recycled, in 15 years, Puerto Carreño could avoid sending 29,231.3 tons of waste to landfill.

Furthermore, the 2020–2035 trends of population and recyclable waste production were extrapolated, assuming a constant per capita waste production and the waste recyclable fraction (~61% in our study) throughout the years to calculate the sanitary landfill lifetime gain if a 100% recycling policy in Puerto Carreño would be performed from 2023 onwards. Supplementary Figure S1 shows the corresponding calculation: the lifetime of the sanitary landfill could reach 2071 instead of 2042, the legal end of the environmental license for El Merey sanitary landfill, with approximately 157,000 tons of waste accumulated (see Supplementary Figure S1). El Merey sanitary landfill's lifetime could thus be doubled (+30 years extra) if all the recyclable waste from 2023 would be recycled instead of being sent to the landfill.

3.3. Discussion

As noted above, this characterization indicates that the great majority of waste produced in Puerto Carreño (61%) is recyclable. However, at present, rather than the waste being used for agricultural or energy purposes, it is disposed of in an inadequate landfill (Figure 1). Moreover, this characterization allows us to optimize the collection of given recyclable materials: for instance, higher-than-average amounts of plastics and cardboard can be collected through the commercial route (Route E, Figure 2) while organic waste for composting can be collected on routes C and D. In general, each waste-collection route has large amounts of recyclable waste, varying between 50% and 68% depending on the route (Supplementary Table S1).

The per capita production of solid waste in Puerto Carreño based on company reports ($SWP_{company} = 0.887 \frac{kg}{capita/day}$; EMPCA, pers.comm.) is unlikely to be accurate, given that the waste management agency does not own a reglementary weighing machine and is likely overestimating other estimates at the departmental or national level; ref. [10] estimated the solid waste production to be less than 0.64 kg/capita/day in almost all departments of Colombia, ref. [2] estimated a range of 0.50–0.99 kg/capita/day, and ref. [35] estimated an average of 0.54 kg/capita/day for Colombia. This estimate ($SWP_{ourstudy} = 0.504 \frac{kg}{capita/day}$) aligns with the previous rough estimates, particularly given that Puerto Carreño, as a municipality with lower-than-average social and economic conditions, produces less waste on average than better-off municipalities.

Comparing this estimate with the recyclable waste data recompiled by CONPES (2016) [5] for the main cities of Colombia (Bogotá, Medellín, Barranquilla, and Cali), this study establishes that Puerto Carreño produced relatively more paper, cardboard, plastic, glass, and metals, and relatively less organic waste than these main cities (see Supplementary Figure S2). The difference in the estimates is likely to have two causes: (i) the socioeconomic dynamics of this small urban-rural municipality, where people reuse the organic waste in their households for gardening and farming and (ii) different estimation methodologies (in-situ characterization vs. local reporting).

Focusing on the recyclable part of waste collection, this study found that the implementation of selective routes is a feasible and relevant option for the municipality. These

selective routes, while maintaining the usual operating costs, can be included in the collection service by replacing a certain number of times per week that the vehicle collects waste and takes it to El Merey landfill with collections of recyclable inorganic waste and recyclable organic waste, in a differentiated manner.

Given the weekly waste production data and the percentage distribution obtained by the characterization, an optimal organization of the collection routes is calculated (Table 1): (i) four collection routes for organic recyclable waste, (ii) three collection routes for inorganic recyclable wastes, and (iii) five collection routes for non-recyclable wastes, which can be mapped out in a new integrated solid waste management plan (known as a PGIRS in Colombia).

Table 1. Distribution of the number of solid waste-collection routes as a function of the utilization potential and the capacity of the collection vehicle.

	Weight of Total Solid Waste (tons)	**Weight of Recyclable Organic Waste (tons) 33%**	**Weight of Recyclable Inorganic Waste (tons) 28%**	**Weight of Non-Recyclable Waste (tons) 39%**
Day	9.24	3.0492	2.5872	3.6036
Week (Monday–Saturday)	55.44	18.2952	15.5232	21.6216
Number of trips required per week	12	3.96	3.36	4.68
Approximation of the number of trips		4	3	5

Finally, management recommendations are provided based on the main problems analyzed in situ, the possible solutions, and the benefits, as well as a classification of their importance. Problems were categorized as high priority or medium priority based on whether their solutions are urgent in the short or medium term, respectively (Table 2).

The solutions suggested are based on the possibilities for the Colombian territory and the national regulatory framework [5], which lead to several benefits: legal compliance, formalization of recyclers (noting that recyclers are mostly members of the indigenous community), increasing the jobs linked to recycling activities, economic optimization of waste collection bills, an increase in the useful life of the landfill, and reduction of associated contamination linked to waste disposal and production.

The objective is to support the development of a circular economy in Puerto Carreño, promoting interdisciplinary solutions that contribute to the proper management of solid waste, and to generate economic, social, and environmental benefits from waste, from its production until its proper final disposal [36,37].

Table 2. Management recommendations scheme describing the main problems found, the proposed solutions considering the reglementary framework, and the associated benefits of an adequate solid waste-management strategy, including indigenous community inclusion.

	Problematic	**Proposed Solutions**	**Benefits**	
High Priority	Presence of indigenous community in sanitary landfill and throughout the collection routes	Indigenous community recognition as Occupational Recycling, to start their formalization process	Creation of companies, social inclusion and dignification of recycling work carried out by indigenous communities	Decrease in the amount of solid waste entering the sanitary landfill, which contributes to reduce the environmental pressures on landfill and can prolong its useful life
	Lack of updating of solid waste management plan (PGIRS)	Update the baseline of the PGIRS for the formulation of a new document that includes the inclusive recycling program and selective routes	Formulation of plans and projects that contribute to the improvement of the comprehensive solid waste management system	

Table 2. *Cont.*

	Problematic	Proposed Solutions	Benefits	
	Lack of selective routes of collection and transport	Establishment of collection and transport routes separately: collection and transport of recyclable waste for indigenous communities and collection and transportation route for the useful organic material	Decrease in informal work and working of minors	Decrease in accidents and affectations to the health of the indigenous recycler community
Medium Priority	Absence of infrastructure for recycling	Establishment of recycling warehouses with machinery to separate and prepare the usable material for its commercialization		
	Inadequate separation in the source of origin of solid waste	Sensitization and awareness campaigns to users of the public cleaning service for the correct separation of solid waste and the proper use of the recollection routes	Avoid the separation of solid waste in public space by contributing better aesthetic aspect of the region	Strengthen the economic and environmental aspects of the waste value chain
	Final disposition in sanitary landfill, inadequately due to lack of machinery and instruments of measurement	Purchase and installation of industrial weighing machine for the appropriate weighing of solid waste that entered the sanitary landfill	Reduction of invoicing of the public cleaning service in terms of its final disposition	Avoid sanctions, closures, or legal inquiries for non-compliance with the provisions of regulations and environmental license

4. Conclusions

Analyzing more than 400 kg of solid waste samples across the highly vulnerable capital municipality of Puerto Carreño in Vichada, Colombia, the per capita production of solid waste was quantified at 0.504 kg/capita/day, a figure comparable with those found for other cities with similar conditions. In this study, it was found that the great majority of solid waste is potentially recyclable, including recyclable organic waste (33% of solid waste) and recyclable inorganic waste (28%), with only 39% of solid waste being non-recyclable. This study is an urgent wake-up call to formalize the roles of the unofficial waste pickers, who are mostly from indigenous communities, living in highly precarious and dangerous conditions, as well as to implement other key waste management recommendations. In order of short to medium-term priorities, the following actions are recommended: provision of basic industrial devices to transport, separate, and weigh the waste; introduction of selective routes to collect certain types of recyclable material; upgrading the El Merey landfill to meet legal requirements; the creation of a sustainable value chain, including indigenous leadership in waste separation; the organization of awareness campaigns about waste; and the creation of a new comprehensive solid waste-management plan.

The recommendations are standard and have been shown to be cost-effective measures in economic, environmental, and social terms because the current model of waste disposal in an open-air landfill, generalized in Colombia, is not environmentally sustainable and even less socially sustainable because of the precarious conditions for waste pickers [37–39], who, as noted, are mostly from the indigenous communities in Puerto Carreño.

To enhance planning on solid waste management in tropical municipalities, this study provides an easy-to-apply methodology that can be replicated in different cities of Colombia and the tropics to improve solid-waste management and the associated sustainable development goals. It is of vital importance to understand the type and amount of waste produced in a community to focus on circular economy strategies that consider the raw materials that can be generated from solid waste.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142416339/s1.

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

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