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Implementing Circular Economy Techniques for the Optimal Management of Recyclable Solid Waste Using the M-GRCT Decision Support Model

Camilo-A. Vargas-Terranova [1], Javier Rodrigo-Ilarri [2,*], María-Elena Rodrigo-Clavero [2] and Alejandro Parra-Saad [1]

[1] Programa de Ingeniería Ambiental y Sanitaria, Universidad de La Salle, Carrera 2 # 10-70, Piso 6-Bloque A, Bogotá 111711, Colombia
[2] Instituto de Ingeniería del Agua y Medio Ambiente (IIAMA), Universitat Politècnica de València, 46022 Valencia, Spain
* Correspondence: jrodrigo@upv.es

Abstract: This article analyzes the implementation of a circular economy model for the management of reusable solid waste in the Colombian municipalities of Arbeláez (province of Cundinamarca) and Tibasosa (province of Boyacá). The analysis is conducted using M-GRCT, a circular economy decision support model for the design of recyclable waste management systems in low-income municipalities. The model allows for performing calculations on a set of two scenarios integrating a sociocultural dynamics assessment—this being a characteristic feature of this type of municipalities. Results show that both the linear and circular models of waste management are economically viable. However, the particular conditions of each municipality, the tariff system, the number of subscribers and the variations in costs and inflation in each municipality affect the results of economic viability. In addition, the waste production scale and the volumes of recoverable waste also affect the results. All these factors are reflected in the scenarios analyzed. In terms of economic viability, the circular model presents better results in Arbeláez, while in the municipality of Tibasosa, the best results are obtained with a linear economy approach.

Keywords: circular economy; solid waste management; recycling; environmental management

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1. Introduction and Objectives

The decrease in natural resources and the increase in waste generation have led to the emergence of the concept of a "circular economy" as a new paradigm opposed to the standard "linear economy" [1]. However, the core ideas of the circular economy emerged in the 1960s and have been discussed ever since [2].

Despite all the existing studies and research, the circular economy does not have a rigorous and unequivocal definition [3]. In fact, more than a hundred definitions have been compiled and all with a certain degree of ambiguity [4].

In practical applications, the circular economy focuses on improving product value chains through reduction, reuse and recycling strategies. Circularity strategies range from expanding and/or intensifying the use of products (goods and services) to recycling materials and even landfill mining [5].

Several economies, such as the European Union, Japan and China, have incorporated the circular economy into their environmental and economic growth policies [6], considering it one of the fundamental pillars of sustainable development [7,8].

Currently, there is an open debate on the relationship between the circular economy and sustainability, the different ways to promote it and the crucial sectors for its implementation [1]. Some authors conclude that the only possible way to improve environmental quality is to increase the rate of recycling [9], since waste has a value other than zero and can generate new material for new production/consumption activities [10].

In Colombia, the progress in the implementation of the circular economy in recent years has been increasing in accordance with what is described in the 2019 Circular Economy Strategy [11]. However, there are some obstacles that deserve to be analyzed and overcome [12]: (i) the deficiency of public policies established to encourage recycling; (ii) the high cost of investment in technology to implement remanufacturing, redesign, reuse strategies; and (iii) the lack of inclusion of recyclers in the entire production chain, an essential role in the use of waste that goes unnoticed by the society and by regulators.

Some studies highlight the importance of promoting separation at the source, not only in homes but also in public places [13]. In this way, by implementing circular economy strategies within the entire exploitation cycle, both the environmental and financial performance would be greater by having more material.

In South American countries, materials such as copper and aluminum are obtained largely from the use of electrical and electronic waste, through what is called "urban mining" [14]. However, the extractive industry predominates, which is why they emphasize that the recovery of waste as subsequent raw materials depends on profitability and technical feasibility, which begins when the waste is separated, and the technological and financial capacity to take advantage of the waste.

Circular economy models must contemplate strategies, both at the business and institutional level, to extend the useful life of products and dematerialization [15]. When implementing circular economy models, it is necessary to determine the sector to which they are applicable in order to determine the relationships and associations that are essential for these circular models to work. Currently, there are circular economy models in many different fields, such as the economies of developing countries [16], agriculture and livestock [17], wastewater [18], tires [19], industrial processes [20], biomethane [21,22] or waste management [23], among others.

In particular, waste management plays an important role in the implementation of the circular economy [24]. However, the lack of precise information on the actual composition of waste, collection and treatment is one of the main barriers to planning such management [25]. Waste recycling remains challenging for several reasons, such as poor management and compliance, regulatory disparities, lack of infrastructure and the high cost of recycling systems, which can have associated public health and environmental impacts [26].

Despite the existing difficulties, studies and analyses aimed at improving the design of recycling techniques and models have increased in recent years [27,28]. There is even research focused on developing circular economy models for the recycling of very specific waste: construction wood [29], steel [13], carbon fibers [30], electrical and electronic equipment waste [31], construction and demolition waste [32] or textiles [33].

In urban areas, future smart cities are expected to carry out automated recycling of waste, helping the transition toward a sustainable environment [34]. The goal is to achieve an effective classification and separation of various types of waste, so that intelligent and automatic recycling improves the functioning of future cities [35,36].

However, a much more difficult challenge is to enable the emerging economies to achieve the recycling rates of developed countries [37]. There are two fundamental problems that must be solved in order to achieve this goal: a deficient waste management system [38] and low efficiency in its treatment [39]. Currently, the recycling efforts and circular economies in Latin America are still under development [40]. Specifically, in Colombia, the challenges in implementing adequate MSW management systems are due to financial sustainability, inclusive recycling and the current legal framework [41].

Considering the aforementioned difficulties, this article analyzes, at a theoretical and practical level, the implementation of a circular economy model for the management of reusable solid waste in the Colombian municipalities of Arbeláez (province of Cundinamarca) and Tibasosa (province of Boyacá). The results obtained provide the first attempt to improve the municipal solid waste management system under circular economy paradigms in the region.

2. Materials and Methods

2.1. DATA4: The M-GRCT Computer Support Tool

This research was conducted using M-GRCT [23], a dynamic circular economy model for the optimal design of waste management systems in low-income municipalities. Based on the conceptualization of the M-GRCT circular economy model, the DATA4 computer tool was developed. DATA 4 allows a comparison of the current (linear) economic model and the circular economy model in the management of usable solid waste. This tool compares two scenarios determining the viability of the model considering both the environmental and financial perspectives.

Scenario 1 includes municipalities that do not have the physical infrastructure and machinery necessary to manage recyclable or reusable waste. These municipalities are considered as small or medium collectors. Scenario 2 corresponds to the municipalities that have collection centers for usable solid waste and that have the appropriate machinery. These municipalities are considered as large collectors. In the case study analyzed in this research, and according to the selection matrix, Tibasosa is classified within Scenario 1 and Arbeláez within Scenario 2.

2.1.1. M-GRCT Environmental Control Procedure

The environmental control procedure considered by the M-GRCT model is shown in Figure 1. This procedure considers a set of criteria in order to compare and determine the feasibility of the two scenarios for the selected municipalities: the projection of recyclers based on the recyclable waste census, the reduction in methane emissions and the reduction in the carbon footprint.

The projection of both official and formalized recyclers between 2021 and 2030 was carried out by analyzing the relationship between the amount of usable solid waste and per capita production, as shown in Equations (1) and (2).

$$PPC = \frac{Per\ capita\ waste\ production\ \left(\frac{\text{kg}}{\text{day}}\right)}{Number\ of\ inhabitants} \tag{1}$$

$$P_R = \frac{Waste\ production\ \left(\frac{\text{kg}}{\text{día}}\right)}{PPC_0} * PPC_1 \tag{2}$$

where PPC = per capita waste production (kg/(day-person)), P_R = recycler's projection, PPC_0 = per capita waste production in the current year (kg/(day-person)) and PPC_1 = per capita waste production in the following year (kg/(day-person)).

To determine the reduction in methane emissions, the LandGEM model was used [42]. This model calculates the methane emissions of the municipalities and their equivalent factor in CO_2 emissions (21 kg CO_2 eq/t), according to the criteria established by the Intergovernmental Panel on Climate Change—IPCC [43]. Equations (3) and (4) were used to calculate methane emissions in the municipalities:

$$CF_{CH4} = E * F_e \tag{3}$$

$$E = E_{CH4} * R \tag{4}$$

where CF_{CH4} = reduction in methane emissions (kg CO_2 eq), E = methane emissions produced by the municipality (kg CO_2 eq), F_e = equivalent factor, E_{CH4} = methane emissions on every final disposal site and R = recyclable waste/ total waste ratio.

To analyze the carbon footprint, the emissions generated by solid waste transportation were taken into account based on the difference between the calculated distance between the collection center and the final disposal site.

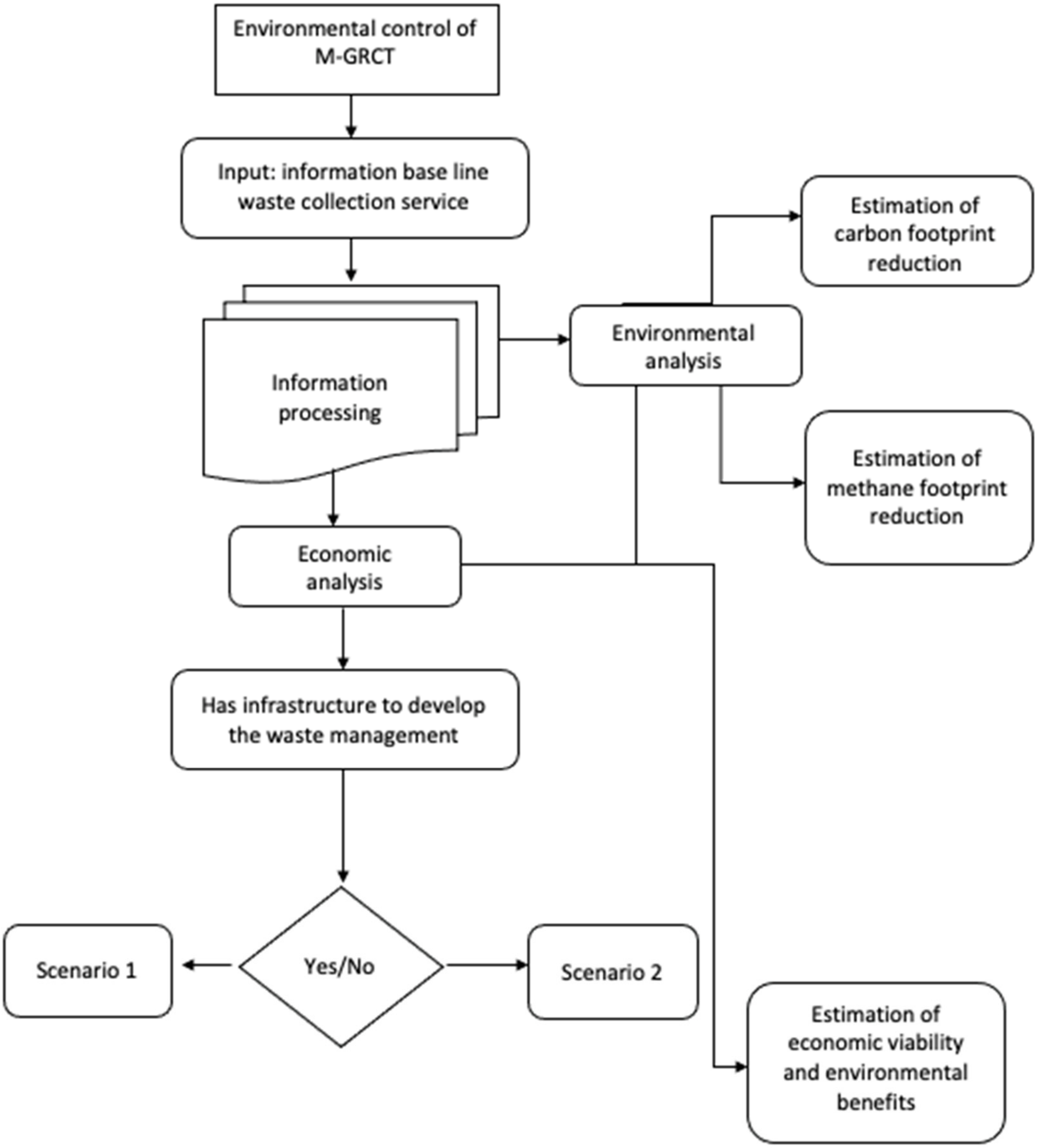

Figure 1. Definition of criteria for the environmental control procedure in the M-GRCT model.

First, the collection frequency and the capacity of the collection vehicles (13 t) were considered. Once the distances were computed, their value was multiplied by the greenhouse gas emission factor established by the Intergovernmental Panel on Climate Change —IPCC (0.68653 kg CO_2 eq/km). Equation (5) shows the methodology of calculation of the transportation carbon footprint reduction:

$$CF_{Tr} = (D_0 - D_A) * F_r * F \quad (5)$$

where CF_{Tr} = transportation carbon footprint reduction (kg CO_2 eq/km), D_0 = distance between the collection center and the final disposal site (km), D_A = distance between the municipality and the collection center (km), F_R = collection frequency and F = emission factor (kg CO_2 eq/km).

To compute the carbon footprint reduction generated by leachates, the weight of processed recyclable waste and the greenhouse gas emission factor established by the Intergovernmental Panel on Climate Change—IPCC (0.022 kg CO_2 eq/t) were used. Equation (6) shows the methodology of calculation of the leachate carbon footprint reduction:

$$CF_L = (Recyclable\ waste\ weight) * F_L \tag{6}$$

where CF_L = leachate carbon footprint reduction (kg CO_2 e) and F_L = greenhouse gas emission factor (kg CO_2 e/t).

Accounting for all this information, the total greenhouse gas footprint reduction can be obtained by adding the three previous terms, as shown in Equation (7).

$$CF_T = CF_{CH4} + CF_{Tr} + CF_L \tag{7}$$

2.1.2. M-GRCT Financial Control

The economic viability criteria of the M-GRCT model [23] were built from two waste management business models. The first model was defined considering a linear waste management strategy, in which the operation consists of a waste collection system and final landfilling without obtaining recycled materials. The second model is based on circular economy techniques, which considers obtaining recycled by-products and their reincorporation into production chains. The model was applied to two municipalities (Arbeláez and Tibasosa), so that, in total, the following four scenarios were analyzed: (i) economic valuation of the linear model in Arbeláez; (ii) economic valuation of the circular model in Arbeláez; (iii) economic valuation of the linear model in Tibasosa; and (iv) economic valuation of the circular model in Tibasosa.

For the construction of the linear scenarios in each municipality, the income and cost figures reported by the mayors of Arbeláez and Tibasosa were used, and the corresponding projections were produced. For the construction of the scenarios of the circular model with M-GRCT, estimates of income, costs and investments were produced for the implementation of recycling plants for the use of recovered materials. In addition, for all the scenarios, the corresponding cash flows were constructed with a 10-year evaluation horizon. A 10% opportunity rate (or minimum expected return) was used. The results are expressed in EUR, taking a reference exchange rate of COP 4545.45 (Colombian pesos) for EUR 1.

In addition, for the calculation of the cash flows, a financing component was assumed through bank credit, since municipalities with low-income levels do not have sufficient resources to carry out the investment with their own resources.

The economic valuation criteria used are the net present value (*NPV*), the internal return rate (*IRR*), the benefit–cost ratio (*BCR*) and the return period (payback). These criteria are widely used in the economic valuation literature for the selection and/or prioritization of projects or investment alternatives [44–48]. *NPV* was calculated according to Equation (8) and IRR according to Equation (9).

$$NPV = -INV_0 - \sum_{j=0}^{N} \frac{C_j}{(1+OR)^j} + \sum_{j=0}^{N} \frac{B_j}{(1+OR)^j} \tag{8}$$

$$0 = \sum_{j=0}^{N} \frac{B_j}{(1+i_{IRR})^j} - \sum_{j=0}^{N} \frac{C_j}{(1+i_{IRR})^j} \tag{9}$$

where *NPV* is defined as the net value of the future cash flows expressed in the base year, INV_0 is the investment at initial time, C_j is the net balance of expenses in period j, B_j is the net balance of benefits in period j, OR is the opportunity rate for a 10% return value (this percentage is set as a reference, taking into account the average return of investment funds in Colombia), j are the periods of the evaluation time horizon (10 years), and $\Sigma_{j=0}^{N}$ is the sum of the cash flows expressed in the base year. On the other hand, i_{IRR} is the internal return rate and is defined as the rate that converts the NPV to zero and represents the rate at which the investment returns. The IRR is calculated through interpolation using the input data to calculate the NPV.

To estimate the benefit–cost ratio (B/C), Equation (10) was used:

$$B/C = \frac{\sum_{j=0}^{N} \frac{B_j}{(1+TO)^j}}{\sum_{j=0}^{N} \frac{C_j}{(1+TO)^j}} \tag{10}$$

where B/C represents the benefits obtained for every EUR of cost in the operation and is defined as the quotient of the present value of income over the present value of costs.

To estimate the payback period, Equation (11) was used. Payback represents the period (years) in which the investment is recovered:

$$Payback = A_{n-1} + \frac{FC_j}{FCa_{j-1}} \tag{11}$$

where A_{n-1} is the number of the immediately preceding period until the initial outlay is recovered, FC_j is the cash flow value in the period in which the initial outlay is recovered, and FCa_{j-1} is the value of the cash flows accumulated in the immediately preceding period until the initial disbursement is recovered.

These economic evaluation criteria must be compared with a set of standard decision criteria about the viability of each scenario. The following three criteria were considered in the analysis:

- A positive value of NPV must be verified to validate the decision to accept the implementation and operation of the business model, whether it is (i) a waste treatment line with final disposal of waste without further use or (ii) a circular economy management model with use of recyclable inorganic waste.
- Another analysis must be conducted based on the value of IRR. The decision criterion is based on the comparison of the IRR with the OR, validating the decision to accept the circular model if IRR > OR.
- Finally, as a third criterion, it must be verified that B/C > 1, which indicates that each EUR allocated to the cost is covered by the income.

The return period does not have a standard of comparison, since it indicates the period of time in which the investment is recovered, which is a sign of the maturity time of the investments. Table 1 shows the possible results of decision criteria from the application of the NPV, IRR and B/C ratio criteria as defined above.

Table 1. Decision criteria over the economic viability of the economic investment alternatives.

NPV Criterion	IRR Criterion	B/C Criterion
NPV > 0 ⇒ Acceptable	IRR > OR ⇒ Acceptable	B/C > 1 ⇒ Acceptable
NPV < 0 ⇒ Refusable	IRR < OR ⇒ Refusable	B/C < 1 ⇒ Refusable
NPV = 0 ⇒ Indifferent	IRR = OR ⇒ Indifferent	B/C = 1 ⇒ Indifferent

2.2. Selection of Municipalities

In Colombia, the municipalities are classified through six categories, depending on the number of inhabitants and the average per capita income. In the country, almost 90% of the municipalities are in the fourth, fifth and sixth categories. These municipalities are the ones with greatest difficulties in the comprehensive management of the public sanitation service, especially in the recycling component [49].

The municipalities were selected based on a weighted criteria selection matrix (Table 2) in which the following four components were evaluated:

- administrative component: existence of a CSWMP and implementation of strategies for the use of waste in the municipal development plan;
- environmental component: existence of a waste collection and classification center;
- economic component: inclusion of recycling activities in the municipal budget and in the financial projections of the comprehensive solid waste management plan (CSWMP);
- social component: existence of activities carried out by environmental reclaimers with citizen participation in recycling activities.

Table 2. Weighted criteria municipality selection matrix.

Component	Criterion	Scale	Value
Administrative	The municipal development plan includes strategies for the management of usable solid waste	Yes	3
		No	1
	The municipality has a comprehensive solid waste management plan	Yes	5
		No	1
Environmental	The municipality has a collection center for reusable solid waste	Yes	10
		No	1
	The municipality identifies and/or classifies reusable solid waste	Yes	3
		No	1
Economic	Within the municipal budget, the collection of usable waste is considered	Yes	5
		No	3
		Unknown	1
	The financial projection of the CSWMP includes income from the activities carried out by recyclers	Yes	10
		No	1
Social	The collection of reusable solid waste is carried out by associations of recyclers or professional recyclers	Yes	10
		No	1
	The participation of the population located in both municipal urban areas and rural areas is constant and inclusive	Yes	3
		No	1

Taking into account this selection matrix, a total set of six municipalities were analyzed in this study. Finally, the municipalities of Arbeláez (located in the department of Cundinamarca, population = 10,005 in 2018) and Tibasosa (located in the department of Boyacá, population = 11,023 in 2018) were selected, obtaining a rating of 50 and 45, respectively. Their location within Colombia is shown in Figure 2.

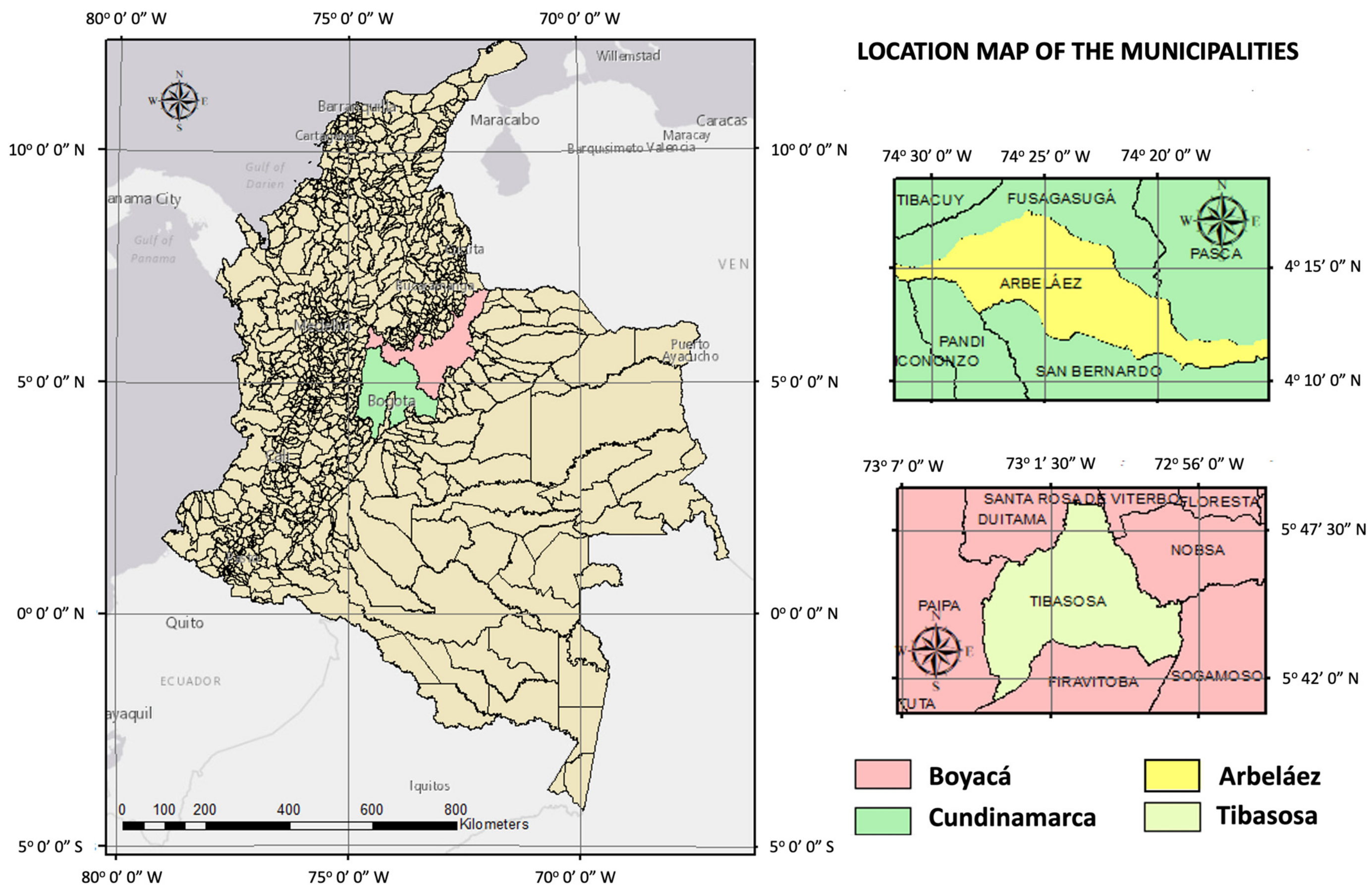

Figure 2. Geographic location of the municipalities of Tibasosa and Arbeláez within the regions of Cundinamarca and Boyacá (Colombia).

2.3. CSWMP Evaluation

The comprehensive solid waste management plans (CSWMP) were evaluated through a SWOT analysis, identifying the weaknesses, opportunities, strengths and threats related to the population, service operators and the municipal administration in terms of the public cleaning service (Table 3).

Table 3. CSWMP evaluation—SWOT matrix.

Strengths	Weaknesses
S1. Control in the provision of the public cleaning service S2. General information of each activity in solid waste managementS3. Definition of solid waste collection routes	W1. The information is not updated regularly W2. Limitation in the budget for the development of CSWMP and for the development of activities W3. Failure to meet the proposed goals
Opportunities	**Threats**
O1. Offer of recycled waste to the community or external actors O2. Participation of the urban and rural population in waste management O3. Introduction of recycled waste into new production chains	T1. Limitations of landfills' capacity and short useful life T2. Projection error due to an increase or decrease in the number of inhabitants in the municipality T3. Non-participation of social actors in awareness campaigns

The information collected from the CSWMP was the main input for the diagnosis and elaboration of the different projections within the model. However, some of these plans do not have all the information required for the application of the model, and in some cases, this information was not updated, so primary sources of information were used. To obtain this information, formal requests were made through surveys and fieldwork, establishing face-to-face communication with the municipal public service companies. Annex A in Supplementary Materials presents the checklist used to collect the information.

3. Results

3.1. MGRCT Environmental Control in Municipalities

3.1.1. Annual Generation of Recyclable Waste

The municipality of Tibasosa is classified as Scenario 1. The trend in the annual generation of recyclable solid waste shows similar percentages for plastic, paper, cardboard and glass and, to a lesser extent, for metal. Moreover, in the municipality of Arbeláez, classified as Scenario 2, there is evidence of a greater generation of plastics, followed by non-iron metal, cardboard, glass, paper and, finally, iron metal.

The comparison between the annual production of recyclable waste (2021–2030) and its average composition on both municipalities is shown in Figure 3. The total production of recycled waste is higher in Tibasosa than in Arbeláez. Tibasosa produces around 30 t/year of paper, cardboard, plastic glass and non-ferrous metal, while in Arbeláez, the production of all these components is lower than 20 t/year (except for plastic, for which the annual production is higher than 50 t/year).

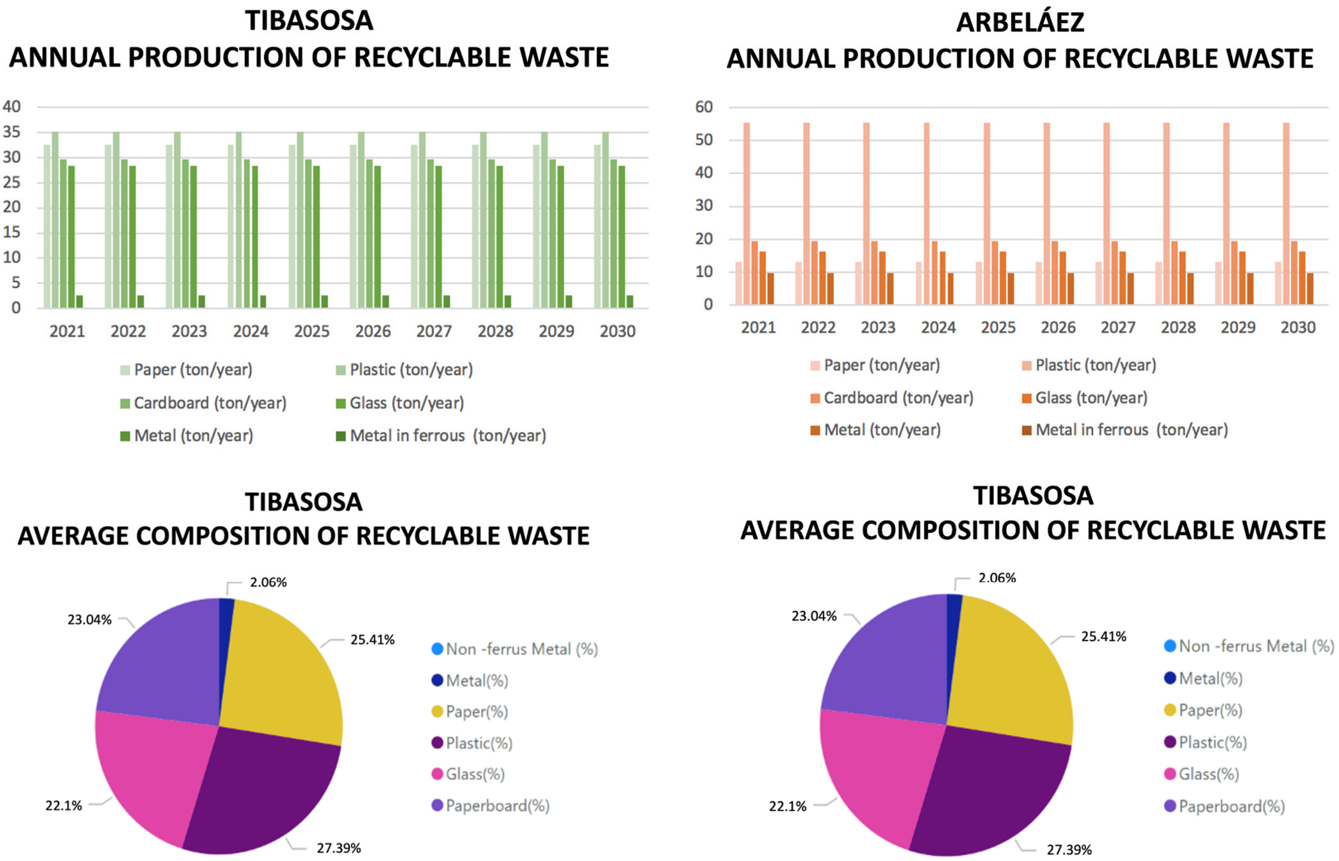

Figure 3. *Cont.*

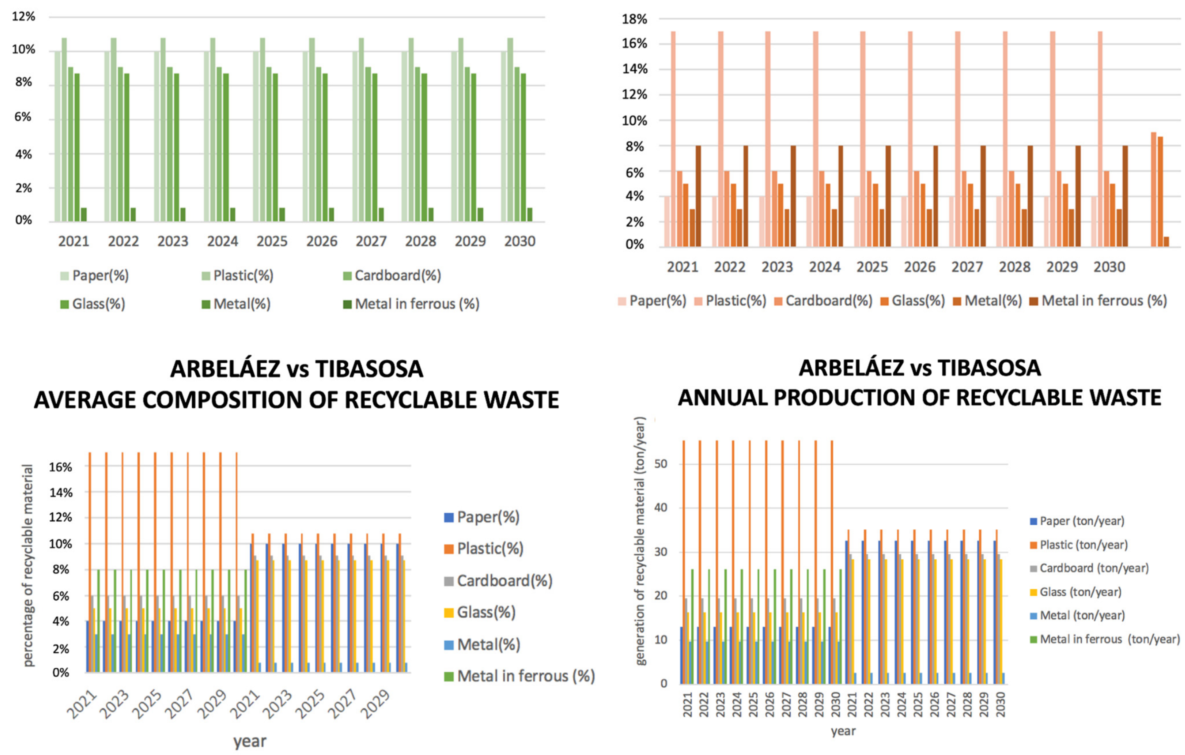

Figure 3. Recyclable waste production and characteristics (**left**) Scenario 1: Tibasosa; (**right**) Scenario 2: Arbeláez.

The average composition of recycled waste in Tibasosa shows that the amounts of every component are equally distributed between paper (25.41%), paperboard (23.04%), plastic (27.39%) and glass (22.10%). Only a very small amount of metal (2.06%) is found.

However, in Arbeláez, the amount of the components of waste is not equally distributed. Higher amounts of plastic (39.53%) are found together with non-ferrous metal (18.60%), paperboard (13.95%), glass (11.63%), paper (9.30%) and ferrous metal (6.98%).

3.1.2. Projection of the Number of Waste Recyclers

The projection for waste recyclers in the municipality of Tibasosa for 2030 is approximately 17 professional recyclers and 20 formalized recyclers. A tendency to increase by one recycler per year for each type of recycler was observed. For the municipality of Arbeláez, according to the projection of recyclers, an increase of 1 recycler per year was observed, although the total number of recyclers is lower than in the municipality of Tibasosa, with a total of 13 professional recyclers and 15 formalized recyclers. The evolution of the total number of recyclers in both municipalities is shown in Figure 4.

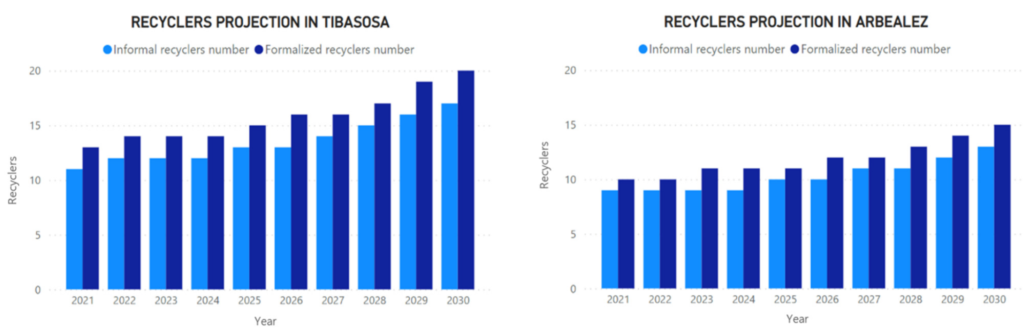

Figure 4. Projection of the number of waste recyclers. (**left**) Scenario 1: Tibasosa; (**right**) Scenario 2: Arbeláez.

3.1.3. Annual Methane Emissions Reduction

For both municipalities of Tibasosa and Arbeláez, a tendency to reduce methane emissions was observed. This reduction is justified by the lower amounts of reusable solid waste, paper and cardboard that are finally disposed of in the sanitary landfill when recovered in the classification plant. Figure 5 shows the estimates obtained by the M-GRCT model in the 2030 horizon.

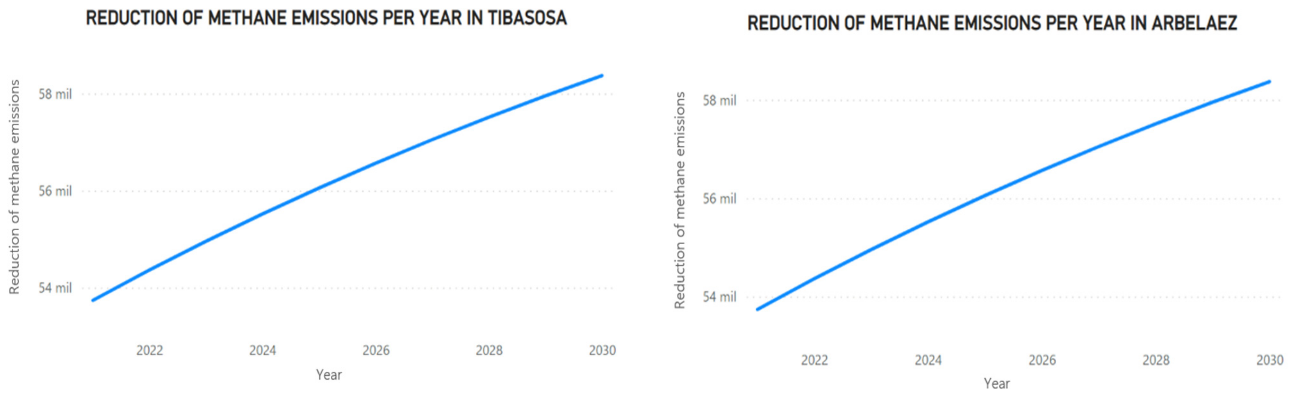

Figure 5. Methane emissions in sanitary landfill reductions (**left**) Scenario 1: Tibasosa; (**right**) Scenario 2: Arbeláez.

3.1.4. Annual Carbon Footprint Reduction

The reduction in the annual carbon footprint due to transportation, generation of leachate and methane emissions is mainly due to the lower distances traveled by the collection trucks and the lower amount of solid waste that will reach the landfill from the collection centers. Figure 6 shows the trend in the reduction in the annual carbon footprint for the municipality of Tibasosa and Arbeláez.

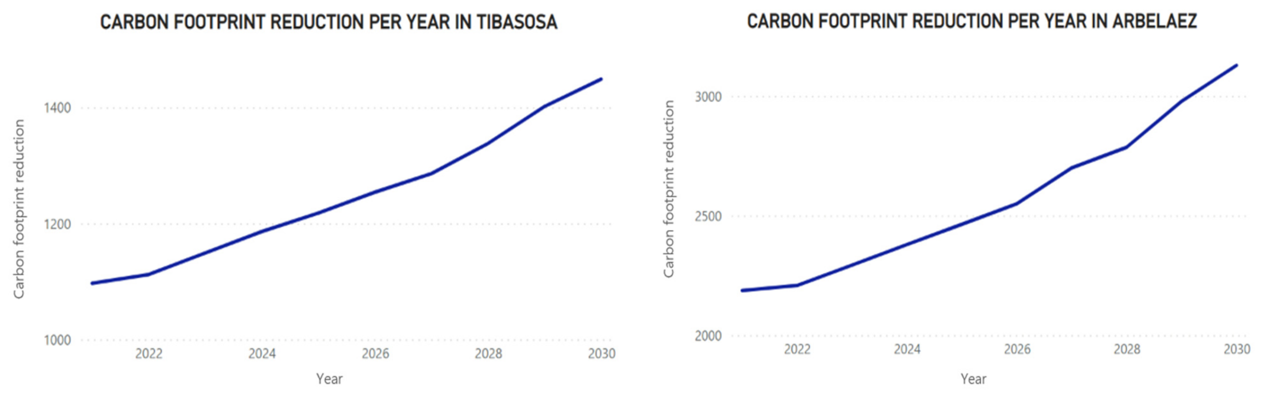

Figure 6. Carbon footprint annual reduction (**left**) Scenario 1: Tibasosa; (**right**) Scenario 2: Arbeláez.

3.2. M-GRCT Financial Control in Both Municipalities

Table 4 records the cash flow inputs and reference values in each scenario used to provide the economic projections considered by the M-GRCT model.

The results of the financial evaluation of each municipality, when operating in the conventional way (linear model) and when implementing a business model based on the management and use of recyclable inorganic waste (circular model), are shown in Table 4.

The results show that the highest NPV is found for a linear scenario in Tibasosa (EUR 325,415), while for a circular economy scenario, the NPV is lower (EUR 109,398). However, for the municipality of Arbeláez, the highest NPV is found for a circular economy scenario (EUR 180,494), and this value is lower under a linear management model (EUR 110,172).

Table 4. Evaluation criteria of the linear and circular management models (*M-GRCT*).

Municipality	**Arbeláez**		**Tibasosa**	
Model Scenario	Linear Scenario 1	Circular Scenario 2	Linear Scenario 3	Circular Scenario 4
Evaluation Criteria				
NPV	EUR 110,172	EUR 180,494	EUR 325,415	EUR 109,398
IRR	34.2%	33.4%	77.6%	26.7%
B/C	EUR 0.00035	EUR 0.00054	EUR 0.00038	EUR 0.00045
Payback (years)	6.7	8.6	2.6	9.8

Note: NPV and B/C in EUR; NPV: Net Present Value; IRR: Internal Return Rate; B/C: Benefit–Cost Ratio; Payback: Return Period.

It was observed that the highest recycling rates in both municipalities were found in plastic. Recycling efficiencies of 17% in Arbeláez and 10.8% in Tibasosa were determined by the M-GRCT model. Moreover, both municipalities showed a similar annual amount of recyclable waste disposed in landfills (407.6 t/year in Arbeláez and 439.3 t/year in Tibasosa). However, there was a notable difference in the total incomes for cleaning services when comparing the values in both municipalities (COP 13,160,986 in Arbeláez and COP 143,886,022 in Tibasosa), as shown in Table 5.

Table 5. Cash flow inputs and reference values in each scenario.

	Arbeláez	**Tibasosa**
	(Linear Model)	**(Circular Model)**
Recycling rate (%)		
Paper	4.0	10.0
Plastic	17.0	10.8
Paperboard	6.0	9.1
Glass	5.0	8.7
Metal	3.0	0.8
Non-iron metal	8.0	0.0
Other information about recycling		
Weight of reusable waste stored in landfills (t/year)	407.6	439.3
Rate of rejection in classification plants (%)	0.2	1.0
Number of official recyclers (#people)	6	5
Number of recycler associations (#people)	0	5
Number of selective collection routes	1	0
Cleaning service basic characteristics		
Total annual income (COP)	13,160,986	143,886,022
Distance from the centroid to the landfill site (km)	99	28
Number of collecting vehicles	253	284
Waste collection frequency (#times/week)	4	4
Weight of solid waste stored in landfills (t/year)	948	1116
Classification and recycling facilities		
Is the facility available?	No	Yes
Number of recycling facilities (Area < 150 m^2)	0	1
Number of recycling facilities (151 m^2 < Area < 999 m^2)	0	0
Number of recycling facilities (Area > 1000 m^2)	0	0
Additional information for the estimation of cash flow projections		
COP to EUR exchange rate	4545.45	
Inflation rate	4.17%	
Opportunity rate	10%	

Note: Figures are given on the base year.

4. Discussion

From the environmental control perspective, the four factors evaluated show substantial improvements and benefits with respect to the solid waste management. Regarding the generation of waste, a similar behavior is observed (Figure 3), taking into account that the two municipalities are included in different scenarios, as Arbeláez is considered a medium producer and Tibasosa a large producer.

Regarding recyclers, although the Colombian regulation is aimed at legally formalizing recyclers in order to have greater control of the reuse activity and provide labor and economic guarantees, this has not led to the expected results, and the process is very slow. Therefore, in the modeling, a distinction is made between formalized recyclers and professional recyclers. The results show that it is evident that the recyclers will gradually increase over time to enhance the use of solid waste. All of this promotes a more solid economic activity that will allow the generation of employment in these municipalities.

The model predicts a clear reduction in methane emissions. According to the projection made, this reduction is due to the decrease in cardboard and paper waste that would be disposed of in a sanitary landfill. With the implementation of recycling techniques, the reuse of these types of waste will be increased in both municipalities.

The model also predicts a reduction in the carbon footprint for both municipalities. This reduction includes methane emissions, the generation of leachate and emissions produced by transportation. The reductions induced by the effects of the implementation of recycling techniques on transport are due to the fact that the inorganic solid waste will have a classification site, and the collection centers will be located at no more than a 5 km distance from the center of the urban area, so the distance traveled until its final disposal will decrease. On the other hand, with time, the vehicle fleet will be changed into one with better technology, helping reduce the emissions, as shown in Figure 6.

Regarding financial control, the net present value in all cases is positive. However, an important difference is observed when comparing the results obtained for the municipalities of Arbeláez and Tibasosa. In Arbeláez, the implementation of the circular waste management model generates a higher NPV (NPV = EUR 180,494), that is, greater net benefits are generated than expected a priori.

However, in Tibasosa, the opposite occurs, and the current system of collecting and disposing of waste in landfills without reusing it turns out to be the best alternative from the economic point of view ((NPV = EUR 325,415), which is 2.9 times higher than the NPV of the circular model in this municipality (EUR 109,398)). This result is justified because, in this scenario, no new investments are required, since the implementation of a waste processing and utilization plant is not necessary, which translates into a lower cost structure.

In addition, the income from the waste collection fee and other incomes derived from the transfers from the National Participation Fund that Tibasosa receives from the Colombian national government are much higher than those registered in Arbeláez because the municipality of Tibasosa has a larger population, which means a higher proportion of subscribers to the waste collection service.

Regarding economic viability, the results show that the IRR, both in the linear model and in the circular model, has a similar behavior in the municipality of Arbeláez, registering returns on investment of 34.2% and 33.4%, respectively, widely exceeding the expected minimum profitability (OR = 10%). These results infer the capacity of the circular model to generate higher profits, since by requiring a higher level of investment (EUR 123,605 more than in the linear model), the returns on investment are still very similar, showing a difference of less than 1% between them. In the case of the municipality of Tibasosa, the IRR in the circular model is 26.7%, showing a similar behavior to that of the circular model in Arbeláez.

This once again demonstrates the economic viability of the model with the reuse of waste. However, due to the higher investment requirements and cost structure, the IRR decreases in this scenario. IRR in the linear model is 77.6%, a figure that, although significantly higher, is explained by the lack of investment in this scenario. In this situation, the structural costs are notably lower in relation to the circular scenario in this municipality. The B/C ratio shows very similar results in the four scenarios analyzed, showing a slight difference in favor of the circular models in Arbeláez and Tibasosa. This shows that each EUR of cost is recovered by the incomes derived from the management and use of waste, confirming the economic viability of the implementation of circular economy models in both municipalities. The highest B/C value corresponds to Scenario 2, that is, the circular economy model in the municipality of Arbeláez, in which B/C = EUR 0.00054.

Finally, in relation to the payback of the investment, it is observed that the linear models show a shorter time (6.7 years in Arbeláez and 2.6 years in Tibasosa). As stated above, this is explained, as in Scenarios 1 and 3, no investment outlay is contemplated, since there is no reuse of waste.

On the other hand, in Scenarios 2 and 4, the investment outlay is equal to EUR 55,405 and EUR 36,889, respectively. This investment is used for the construction of the waste recycling plants. Therefore, the return periods are longer (8.6 years in Arbeláez and 9.6 years in Tibasosa). These payback times are considered to be within common recovery intervals [50].

5. Conclusions

The M-GRCT model developed through the DATA4 computer tool for the study of the use of solid waste under linear and circular economy scenarios was applied to Arbeláez and Tibasosa, two municipalities with depressed economies in Colombia. The application of the model presents great advantages both at an environmental and economical level.

The differences assigned in the evaluation criteria for each scenario can be attributed to the variations in the revenue collection capacity, given the different populations affected and the differences in the structure of expenses in each scenario. In addition, the linear model scenarios do not include investments, since the reuse of waste is not going to be carried out. On the other hand, in the circular economy scenarios, the expenses related to the investment necessary to build the waste recycling infrastructures are included.

The results show that both the linear and circular models of waste management are economically viable. However, the particular conditions of each municipality, the tariff system, the number of subscribers and the variations in costs and inflation in each municipality affect the results of economic viability. In addition, the waste production scale and the volumes of recoverable waste also affect the results. All of these factors are reflected in the scenarios analyzed. In terms of economic viability, the circular model presents better results in Arbeláez, while in the municipality of Tibasosa, the best results are obtained with a linear economy approach.

Although the M-GRCT model was originally conceived with the aim of proposing solutions to the problem of comprehensive solid waste management in municipalities with depressed economies, it is possible to use it in groups of municipalities (on a regional scale), even in those cases in which the adoption of the management model at the municipal level is not economically profitable, taking into account the conditions of the defined scenarios. This use of the model on a regional scale should be carried out under conditions similar to those of Scenario 1, in terms of distances to the transformation plant, percentages of rejection and investment in technical machinery.

The M-GRCT model was conceived for the correct management and recovery of municipal solid waste in depressed economies, integrating the recycling process into the traditional municipal solid waste management model and evaluating the components that can be recycled and reintroduced into the production cycle. Future research will focus on the use of M-GRCT for the management of industrial waste, for which the DATA-4 interface must be suitably adapted. For example, in the particular case of industrial waste in Colombia, the adaptation of the model should be carried out in such a way that the three industrial waste management schemes currently considered in the country are taken into account (incineration, final deposition in sanitary landfill and recycling). Currently, in Colombia, only a very low percentage of industrial wastes can be reintroduced into the production cycle through a mechanism known as BORSI (Industrial Waste and By-products Exchange).

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Glossary

BCR	Benefit–Cost Ratio
CFCH4	Reduction in methane emissions (kg CO_2 eq)
CFL	Leachate carbon footprint reduction (kg CO_2 eq)
CSWMP	Comprehensive Solid Waste Management Plan
DATA4	A dynamic tool, which supports the M-GRCT model and allows for developing the economic comparison
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Return Rate
LandGEM	USEPA Model. An automated estimation tool with a Microsoft Excel interface that can be used to estimate emission rates.
M-GRCT	A dynamic circular economy model for the optimal design of waste management systems in low-income municipalities developed by the authors.
NPV	Net Present Value
OR	Opportunity rate
PPC	Per Capita waste Production (kg/(day-person))
PPC0	Per Capita waste Production in the current year (kg/(day-person))
PPC1	Per Capita waste Production in the following year (kg/(day-person))
PR	Recycler's Projection

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