ENFOQUE UTE REVISTA
Facultad Ciencias de la Ingeniería e Industrias

RESEARCH ARTICLE

ENFOQUE UTE, VOL. 17, NO. 1, pp. 23-33, E-ISSN: 1390-6542
RECEIVED MAY 13, 2025; REVISED SEPTEMBER 18, 2025; ACCEPTED OCTOBER 20, 2025; PUBLISHED ONLINE DECEMBER 20, 2025; PUBLICATION DATE JANUARY 1, 2026.

Citation: B. J. Faubla Cusme and J. M. Calderón Pincay, "Multicriteria Analysis for the Solid Waste Management Model in Bolívar Canton," Enfoque UTE, vol. 17, no. 1, pp. 23-33, Jan. 2026, doi: https://doi.org/10.29019/enfoqueute.1186

Multicriteria Analysis for the Solid Waste Management Model in Bolívar Canton

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Abstract — **The purpose of this research was to develop a solid waste management model for the Bolívar canton, considering environmental, economic, social, and technical criteria through a multicriteria analysis approach. The supply chain was characterized through a detailed analysis of the urban solid waste management process in the Bolívar canton, including its different stages and stakeholders. Supply chain flows were defined by identifying and quantifying the waste streams currently circulating within the chain. Finally, the solid waste management model was determined based on the requirements proposed by the AME (Mexico City Association of Solid Waste) in its comprehensive management project for non-hazardous solid waste generated in Ecuador. This research is proposed as a strategic tool for moving toward more sustainable and resilient cities. Consequently, investing in this type of model entails short-, medium-, and long-term benefits, ensuring balanced development across the environmental, social, and economic spheres. The results show that solid waste generation in the Bolívar canton is 0,72 kg/inhabitant/day, with minimal variations across parishes. In the residential sector, generation reaches 0.36 kg/inhabitant/day, equivalent to 50 % of the total. Furthermore, the monthly cost per household for the GIRS (Mexico City Association of Solid Waste) is estimated at USD 6.60. This information is key for planning and optimizing the collection system, contributing to more efficient and sustainable management.**

Keywords: **waste management; supply chain; waste treatment; Ecuador; economic analysis.**

Resumen — **El propósito de la investigación fue desarrollar un modelo de gestión de residuos sólidos para el cantón Bolívar, considerando criterios ambientales, económicos, sociales y técnicos, mediante un enfoque de análisis multicriterio. Se caracterizó la cadena de suministro a través de un análisis detallado del proceso de gestión de los residuos sólidos urbanos en el cantón Bolívar, incluyendo sus diferentes etapas y actores involucrados. Se definieron los flujos de la cadena de suministro por medio de la identificación y cuantificación de los flujos de residuos que circulan en la actualidad dentro de la cadena. Finalmente, se determinó el modelo de gestión de residuos sólidos basado en los requerimientos planteados por la Asociación de Municipalidades del Ecuador en su proyecto de gestión integral de residuos sólidos no peligrosos. Esta investigación se plantea como una herramienta estratégica para avanzar hacia ciudades más sostenibles y resilientes. En consecuencia, invertir en este tipo de modelo implica beneficios a corto, mediano y largo plazo, asegurando un desarrollo equilibrado entre el ámbito ambiental, social y económico. Los resultados muestran que la generación de residuos sólidos en el cantón Bolívar es de 0,72 kg/hab/día, con variaciones mínimas entre las distintas parroquias. En el sector residencial, la generación alcanza los 0,36 kg/hab/día, lo que equivale al 50 % del total. Por otra parte, el costo mensual por vivienda para la GIRS se estima en 6,6 USD. Esta información resulta clave para la planificación y optimización del sistema de recolección, contribuyendo a una gestión más eficiente y sostenible.**

Palabras Clave: **gestión de residuos; cadena de suministro; tratamiento de desechos; Ecuador; análisis económico.**

I. INTRODUCTION

THE collection of municipal solid waste (MSW) worldwide presents a significant challenge due to the variety of sources and the heterogeneous characteristics of this waste [1]. Population growth and excessive industrial consumption have led to a considerable increase in the generation of this waste, making it an increasingly complex challenge [2]. Likewise, the expansion of human activity to virtually every corner of the planet, along with the intensive exploitation of resources, has further aggravated this problem [3].

The responsible use of natural resources and the promotion of sustainable development require coordinated action from the public and private sectors, as well as communities [2]. Therefore, it is essential to implement policies, plans, and programs that promote the proper management of municipal solid waste, a growing problem that is generating great concern [1]. In this context, international organizations play a key role in promoting integrated MSW management at both national and local levels [4]. This management must adopt a holistic approach that considers all stages of the waste life cycle—from its generation to its final disposal—with the objective of generating economic, social and environmental benefits [5].

Between 2002 and 2010, solid waste management in Ecuador was severely deficient, a situation that has not improved

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DOI: https://doi.org/10.29019/enfoqueute.1186
Associate Editor: Freddy Alvarez

significantly to this day. A total of 160 of the country's 221 municipalities lacked adequate systems for final waste disposal, relying instead on open dumps [3]. This practice caused serious environmental impacts, such as soil, water, and air pollution, and jeopardized public health [6]. In contrast, the remaining 61 municipalities had disposal sites, but their management did not meet the required technical standards [1].

In 2016, the Government of Ecuador, through the Ministry of the Environment, launched the National Program for Integrated Solid Waste Management (PNGIDS) [6]. The objective of this program was to strengthen solid waste management in the country's municipalities, promoting a comprehensive and sustainable approach to reduce environmental pollution, improve the quality of life for the population, and protect ecosystems [7]. In the case of Manabí, inadequate solid waste management represents a significant challenge to sustainable development and public health [8].

The lack of adequate infrastructure—such as efficient waste collection, treatment, and disposal systems—has led to the proliferation of open dumps, which pollute the soil, water sources, and air [9]. Furthermore, the absence of effective recycling and environmental education programs limits citizen participation in sustainable practices [2]. Consequently, this problem not only affects the natural environment and the quality of life of residents but also increases the risks associated with vector-borne diseases and the impact of climate change due to greenhouse gas emissions from waste decomposition [10].

As part of the solution to this problem, this article proposes the use of a multicriteria analysis focused on integrated solid waste management, with the aim of optimizing MSW management processes. It should be noted that this model was used to select final disposal sites in urban areas of the Andean region of Ecuador, considering environmental, social, technical, and economic criteria that allowed for the determination of the most viable alternatives for location, coverage, frequency, and improvement of waste management.

According to the above, the Bolívar canton lacks an efficient solid waste management model, as all collected waste is disposed of without any prior use or treatment, leading to a higher degree of solid waste pollution [9]. For this reason, it is necessary to implement a comprehensive urban and rural solid waste management model in the canton to adopt efficient criteria for its proper management, optimize available resources, and ensure compliance with the current national regulatory framework. Furthermore, this research will contribute data to address the lack of studies applied to small cantons in Ecuador with similar circumstances.

II. MATERIALS AND METHODS

A. Characterization of the supply chain

This research was conducted in Calceta, Bolívar canton, Manabí province, Ecuador (Fig. 1).

For this phase, the multicriteria model proposed by [11] was used, focused on the comprehensive management of municipal solid waste. According to this methodology, the first step was to identify the operational processes and the requirements involved in waste management in the Bolívar canton, which include generation, collection, transportation, and final disposal. Generation corresponded to all service users: residential, commercial, industrial, or others, including schools, colleges, public buildings, etc.

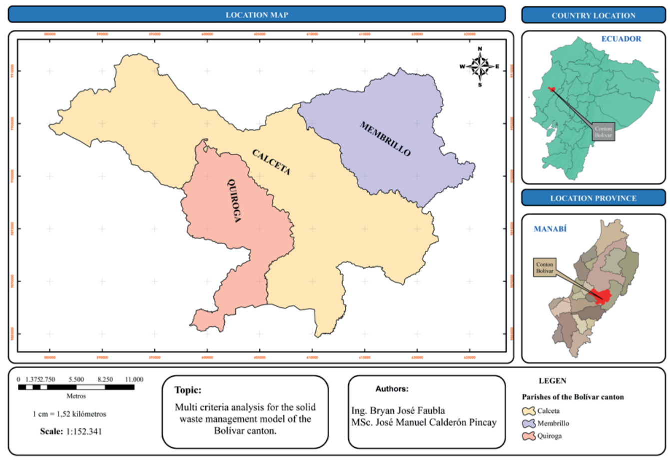

Fig. 1. Location of the study area.

Collection routes were established according to the generation points, and the waste was transported to the final disposal area, jointly managed by three Decentralized Autonomous Governments (GAD): Tosagua, Junín, and Bolívar. Each GAD is responsible for operating the cells for four months a year, distributed over two months per canton on an alternating basis.

Eq. 1 is used to calculate the daily per capita production (DPC):

$$PPC = \frac{Pw}{Np} \qquad (1)$$

Where:

- *PPC* represents per capita production (kg/person·day);
- *Pw* is the daily waste weight (kg/day); and
- *Np* is the number of people.

The equation considers the total population of the canton without distinguishing between the types of waste generators due to the lack of a municipal registry of users who receive waste collection services.

A literature review was conducted to determine the current economic aspects related to solid waste management in Bolívar (municipal GAD database). Likewise, the assigned budget was reviewed, including worker salaries, expenses for tools, vehicle maintenance, and fuel costs, comparing the revenues collected through waste collection fees with the total expenditure [35].

Finally, the environmental conditions of the solid waste management service were evaluated by identifying the environmental aspects and impacts of the process through the application of the Leopold Matrix [12]. The weighting matrix used is shown in Table I.

TABLE I
IMPACT AGGREGATE WEIGHTING (LEOPOLD MATRIX)

Aggregate Impact Weighting		
Negative rating	-	
Irrelevant	0	-25
Moderate	-25	-50
Severe	-50	-75
Critical		≤ -75
Positive rating	+	
Not very important	0	25
Important	25	50
Very important		> 50

The classification scheme presented in Table I establishes a rating system based on a scoring range that differentiates between negative and positive impacts. Irrelevant aspects (0 to -25) are minimal impacts that do not generate significant changes in the environment. These are usually associated with minor and reversible alterations, such as small aesthetic landscape changes or temporary noise emissions. Moderate impacts (-25 to -50) affect certain aspects of the ecosystem or society but do not compromise their stability.

Severe impacts (-50 to -75) represent a considerable level of impact, with medium- to high-magnitude negative effects that may require significant mitigation measures. Critical impacts (≤ -75) are large-scale impacts that can cause irreversible or difficult-to-remedy damage. Finally, other important elements were detailed, such as the general functions and logistical tasks of the supply chain, along with key organizational methods, policies, and procedures regulating MSW management in Bolívar.

B. Definition of supply chain flows

To carry out this phase, the methodology based on the Green Supply Chain approach [13] was used as a reference. This approach combines the SCOR (Supply Chain Operations Reference) model—adapted to sustainable resource and waste management—with specific elements for the integrated management of urban solid waste.

The process began with the identification of the actors within the supply chain, followed by the classification of MSW according to their type (organic, recyclable, non-recyclable, hazardous, etc.) [14]. The stages of the chain were also identified: generation/collection, separation, treatment centers, customers, and final disposal. Each stage involves different actors, such as waste generators and service users.

Subsequently, the supply chain was designed, and its flows were modeled through a graphical diagram [13]. Finally, strategies were defined to improve waste management [15].

C. Multicriteria analysis

The multicriteria analysis considered two options for solid waste management:

- Alternative A – Current System (Linear Model)
- Alternative B – Proposed System (Circular Approach Model)

Four criteria were defined and assigned a weighting based on urgency and estimated impact, with the environmental criterion having the highest percentage (40 %), followed by the economic criterion (30 %), the social criterion (20 %), and the technical criterion (10 %) [34].

To compare the alternatives, value functions were used to transforming the proposed data (costs, percentages, qualitative assessments) into a common scale from 0 to 10, where 0 represents the worst performance and 10 represents the ideal performance, following the scale used by [72]. These values were then rated in a matrix, as shown in Table II.

TABLE II
ALTERNATIVE WEIGHTING MATRIX

Criterion (Weighting)	Subcriterion (Weighting)
Environmental (40 %)	Environmental impact (20 %)
	Utilization rate (20 %)
Economical (30 %)	Annual operating cost (15 %)
	Income potencial (15 %)
Social (20 %)	Job creation (10 %)
	Public health (10 %)
Technique (10 %)	System efficiency (5 %)
	Operational complexity (5 %)

D. Determination of the solid waste management model

The solid waste management model was based on the design of a transfer station, following the methodology proposed by [13], which considers the physical characterization of MSW (including daily weighing of all waste over eight days—excluding the first day's measurement—as well as separation and weighing by waste type) [17], the analysis of waste generation and collection, the selection of the area for the plant, its dimensions, and its economic analysis. These data were used as the foundation for the design of the transfer station [37].

For the selection of the area where the transfer stations will be installed, the methodology of [37] was followed, considering the distance to the final disposal site. The dimensions of the transfer station are linked to the generation of solid waste determined through its physical characterization.

III. RESULTS AND DISCUSSION

A. Generation andCollection

The collection system operates through a door-to-door modality, consisting of collecting waste directly from households and commercial establishments. Fig. 2 shows the collection routes.

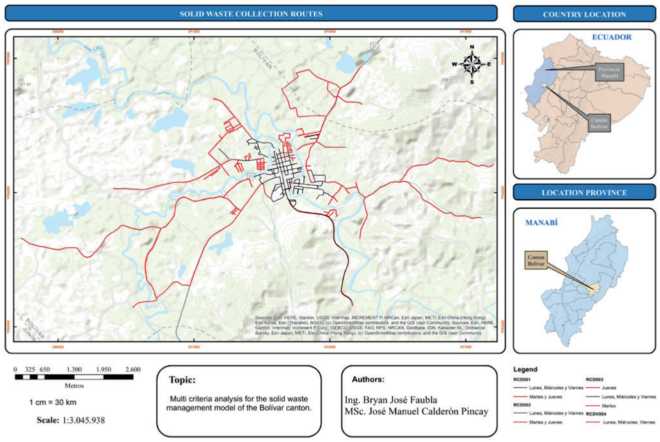

Fig. 2. Collection route map.

Currently, there are three collection vehicles with a capacity of 20 yards and one dump truck with a capacity of 8 m^3, used in the cantonal capital (Calceta). for the rural parishes of Quiroga and Membrillo, one 8 m^3dump truck is used in each parish.

Table III presents the solid waste generation (PPC) per parish in the Bolívar canton.

TABLE III
DAILY SOLID WASTE GENERATION IN THE BOLÍVAR CANTON

Parishes	Population	PPC (kg/person/day)	PRR (kg/day)
Calceta	34 702	0,71	24 711,7
Quiroga	3 552	0,70	2 496,0
Membrillo	3 573	0,82	2 923,3
Total	41 827	0,72	30 131,0

Table III shows that the average per capita production (PPC) in the Bolívar canton is 0,72 kg/person/day, with internal variations among parishes (0,70-0,82 kg/person/day). This variability is associated with cultural factors, collection frequency, seasonal variations, rural characteristics, and waste migration.

Consequently, Calceta generates 82 % of the total solid waste (24 711.7 kg/day), while Quiroga and Membrillo generate 8 % and 10 %, respectively.

The PPC values obtained in the three evaluated parishes fall within the range reported by [14], who notes that rural communities in Latin America generate between 0,4 to 0,8 kg/person/day, depending on socioeconomic level, consumption patterns, population density, and waste management services.

Similar results were reported by [15] in a study conducted in rural areas of Colombia, where an average PPC of 0,56 kg/person/day was found, influenced by limited access to recycling systems and the increasing use of disposable products. Likewise, a PPC between 0,45 and 0,75 kg/person/day has been observed in rural communities in Mexico, with higher values linked to an increased consumption of processed products in households and a low culture of reuse.

In the case of the parish of Membrillo, the fact that it is near the upper limit of the range (0,8 kg/person/day) could therefore indicate a higher consumption of industrialized, packaged, and short-life products, a trend that has extended even into rural areas due to the penetration of formal and informal markets promoting quick consumption. Additionally, communities with lower habits of waste separation and reuse tend to have higher PPC, as potentially recoverable materials end up being discarded.

Furthermore, Table IV shows the generation of household solid waste in the Bolívar canton: 0,36 kg/person/day.

TABLE IV
GENERATION OF SOLID WASTE (RESIDENTIAL)
IN THE BOLÍVAR CANTON

Parishes	Population	PPC (kg/person/day)	PRR (kg/day)
Calceta	34 702	0,37	12 839,74
Quiroga	3 552	0,29	1 030,08
Membrillo	3 573	0,29	1 036,17
Total	41 827	0,36	14 905,99

According to Table IV, the analysis of waste generation considering only household solid waste in the parishes of Calceta, Quiroga, and Membrillo in the Bolívar canton reveals variations in waste generation patterns influenced by factors such as population density, socioeconomic characteristics, and the consumption habits of the inhabitants.

The difference in residential solid waste generation by parish is due, according to [16], to the fact that larger urban centers tend to be the main generators of waste because of their economic dynamics and consumption patterns, compared to rural areas and smaller populations. In this context, [17] and [18] state that residential PPC is closely related to economic income and the level of urbanization of a society, where densely populated urban areas tend to have higher residential PPC than rural areas.

In this context, Table V also shows the coverage of solid waste collection in the Bolívar canton:

TABLE V
COLLECTION COVERAGE

Parishes	Population	Population served	CRC %	CRC % (INEC, 2022)
Calceta	34 702	23 844	69	77
Quiroga	3 552	1 776	50	56

With respect to Table V, the collection model used in the Bolívar canton is the agglomeration model, which means that waste is collected in a mixed form and is not separated at the source. The data provided show the waste collection coverage in the three parishes of Bolívar: Calceta, Quiroga, and Membrillo, as well as the implications of the gaps found between the actual waste collection coverage (WCC) figures and the official estimates provided by the National Institute of Statistics and Census (INEC) in 2022.

These data coincide with those proposed by [19], who indicates that differences between estimated and actual coverage are common in intermediate areas, due to factors such as outdated population censuses, internal migration, and budget limitations of local governments.

Calceta, with a population of 34 702 inhabitants, has a waste collection coverage rate of 69 %, slightly below the 77 % projected by INEC. While it is the parish with the highest coverage within the canton, the 8 % difference reflects logistical and administrative challenges in the provision of the service. Areas with rapid population growth or disordered urban expansion tend to fall behind in basic services, including waste collection. Additionally, in many municipalities in Ecuador and the Andean region, collection systems still face limited operational planning, insufficient infrastructure, and inadequate training of personnel involved.

Waste collection coverage in the parish of Quiroga, which reaches only 50 % of its population, reflects the structural and logistical limitations faced by many rural communities in Ecuador and Latin America. This figure is slightly lower than the national rural average estimated by INEC (56 %). This difference can be attributed to factors such as the geographic dispersion of households, lack of adequate road infrastructure, and limited municipal investment in public services, aspects also highlighted by [13] in their study on waste management in rural areas of the Ecuadorian highlands.

Previous research has also shown that deficient access to waste collection in rural areas is not only due to technical or geographic limitations, but also to prioritization criteria applied by local governments, which tend to concentrate their resources in more densely populated areas or in places with greater social and political pressure. In the rural parishes of the province of Loja, waste collection coverage fluctuated between 40 % and 60 %, with lower values in dispersed communities with difficult vehicle access.

For its part, Membrillo, with only 22 % WCC compared to the 24 % projected by INEC, shows a lower level of coverage, revealing a marked exclusion in access to this basic service, which could lead to serious environmental and health consequences for the community. This difference, although apparently minimal, highlights a concerning situation of exclusion and inequality, which may generate severe environmental and public health impacts [20].

On the other hand, rural waste management services in southern Peru reported coverage levels as low as 20 %, linking this low coverage to budget constraints, geographic inaccessibility, and poor institutional planning. Similarly, in rural communities in Honduras with WCC below 25 %, inadequate waste management contributed to the proliferation of disease vectors and contamination of surface water bodies. In Ecuador, rural parishes in the province of Manabí may have WCC levels below 20 %, reflecting the lack of prioritization by local governments in environmental management.

Table VI below shows the composition of solid waste generated in the Bolívar canton:

TABLE VI
COMPOSITION OF SOLID WASTE GENERATED IN THE BOLÍVAR CANTON

Waste type	Percentage	Amount of waste (kg)
Paper and cardboard	17 %	5 122,3
PET	13 %	3 917,0
Glass	8 %	2 410,5
Metal	5 %	1 506,6
Organic matter	57 %	16 873,7
Hazardous waste	1 %	301,31
Total	100 %	301,131

As shown in Table VI, organic waste represents the largest proportion (57 %) of the total waste generated, which presents an opportunity for the implementation of composting and biodigestion programs. These programs reduce the amount of waste sent to landfills by transforming it into useful products such as compost or biogas [21].

The second most important component is paper and cardboard waste (17 %), which may be associated with the commercial and educational activities of the canton. In this regard, [17] suggests that this type of waste has high recycling potential, allowing for the implementation of selective collection initiatives for its reuse.

PET plastic accounts for 13 % of the waste generated, a significant percentage given that plastics degrade very slowly and have serious environmental consequences [22]. Therefore, proper management is essential to mitigate these impacts.

Glass represents 8 % of the waste generated, possibly related to beverage consumption. Although glass is not biodegradable, it is 100 % recyclable [23], so collection centers are key to maximize its reuse.

Metals (5 %) represent a valuable resource due to their infinite recyclability. This low percentage may indicate that informal selective collection already exists or that metal generation is limited in comparison with other materials [21]; therefore, promoting the formalization of recyclers and metal recovery would contribute both economically and environmentally to the population of the Bolívar canton.

Although hazardous waste represents only 1 % of the total, its proper management is crucial due to its potential to harm human health and the environment.

According to [24], in rural areas of Latin America, hazardous waste—despite its low volume—is particularly problematic due to the lack of infrastructure and the limited training of the population regarding its separation and final disposal. This situation results in cumulative risks, especially when such waste is mixed with household waste. It is worth noting that the percentage of hazardous waste did not exceed 1,2 %; however, poor management led to soil and water contamination, particularly from waste such as batteries, expired medications, and agrochemical containers. The authors concluded that, beyond volume, the danger lies in the toxic, corrosive, or flammable characteristics of these materials.

B. Transportation and final disposal

Urban solid waste is transported from the collection routes to the emergency cells, where final disposal takes place. Through a technical procedure, the waste is deposited in a shared area managed by the association, which alternates its operations every two months among the member cantons (Junín, Bolívar, and Tosagua). The corresponding canton is responsible for the full operation of the cell, including the machinery, materials provided for waste collection, and the operational and technical personnel. The shared area covers a total of 12 hectares; however, only 4,2 hectares are currently in use, as the remaining area is not operational nor suitable for receiving waste from the association.

C. Economic aspects

The operating costs of integrated solid waste management in the Bolívar canton are related to activities such as handling (including machinery and equipment required for collection) and storage (associated with the custody of waste until final disposal). However, transportation costs may vary, as they depend on the number of trips made by the collection vehicles.

Table VII presents the costs associated with the integrated management of urban solid waste in the Bolívar canton:

TABLE VII
COSTS ASSOCIATED WITH THE INTEGRATED MANAGEMENT OF URBAN SOLID WASTE

Description	Quantity	Unit of measure
Waste collected	9 421,3	t/year
Waste disposed of	9 421,3	T
Average distances	3 438	km
Average unit transport cost	3,64	$/km
Fixed cost of waste disposed of	48 600	$/year
Variable costs of waste disposed of	5,16	$/t
Fixed collection costs	472 807,27	$/year
Variable collection costs	50,2	$/t
Total annual operating cost	696 106,60	$/year
Expenses for material purchases	6 399,29	$/year
Total revenue	191 419,47	$/year
Difference in annual operating cost	-504 687,13	$/year
Total monthly operating cost	58 008,88	$/month
GIRS users (INEC, 2022)	8 802	homes
GIRS service cost per family per month	6,6	$/month home

As shown in Table VII, the costs associated with the integrated management of urban solid waste in the Bolívar GAD vary depending on the source of the costs and the amount of waste collected. The values related to treated waste do not apply to the canton, as this process is not currently carried out, nor is any other process that would allow for the proper utilization of the waste generated.

Additionally, Table VIII shows the monthly cost per household for the integrated management of solid waste:

TABLE VIII
PROJECTION OF THE FEE FOR THE MANAGEMENT OF NON-HAZARDOUS SOLID WASTE

Rate summary			
Canton	**Number of GIRS service homes**	**Total cost of the GIRS/month**	**Cost per family/ month**
Bolívar	8 802	$58 008,88	$6,6

According to Table VIII, the monthly fee per household for the integrated solid waste management service is USD 6,6. It is important to note that this amount is based on the total cost of the integrated solid waste management service.

Next, Table IX shows the projected costs of solid waste management:

TABLE IX
PROJECTED COSTS FOR THE PROVISION OF THE GIRS SERVICE

Statement of results	Value
Annual income	191 419,47
Annual expenses	696 106,60
Annual profit	0
Annual difference	-504 687,13

According to Table IX, the total annual operating cost of the integrated solid waste management service in the Bolívar GAD is USD 696 106,60, given that the GAD receives annual revenues of USD 191 419,47 from the National Electricity Corporation (CNEL). This results in a deficit of USD 504 687,13 between expenses and revenues. Additionally, the annual revenues collected for integrated solid waste management represent 27 % of the total annual expenditure, resulting in an economic deficit of 73 %. Consequently, the Bolívar GAD incurs an economic loss of 73 % for integrated solid waste management, equivalent to USD 504 687,13.

D. Environmental aspects

The application of the Leopold Matrix identified that during the stages of waste generation, collection (transport), and final disposal, various negative impacts are generated that affect the environment and public health. These impacts include leachate generation, the production of unpleasant odors, soil contamination, and air pollution.

TABLE X
ENVIRONMENTAL FACTORS EVALUATED IN THE LEOPOLD MATRIX

Environmental factors		
Factors	**Code**	**Score**
Surface water quality	SWQ	-78
Groundwater quality	GWQ	-174
Air quality (gases, particles)	ArQ	-168
Heavy metal soil contamination	HMSC	-156
Organic compound and other contaminant soil contamination	OCSC	-180
Local flora	LFl	-162
Local wildlife	LFn	-162
Risks to human health from vector-borne diseases, exposure to contaminants, and accidents.	RSH	-156
Landscape design	LD	-150
Employment	EMP	168
Effects on the quality of life of local communities, access to resources, and economic activities.	EQL	-78

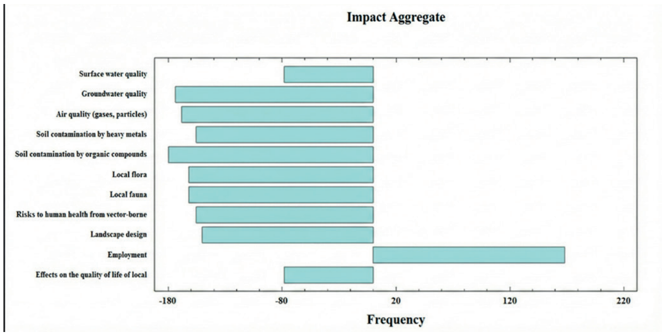

Fig 3. Environmental factors evaluated.

Regarding leachate generation, this is one of the main environmental problems associated with inadequate MSW management, as these liquids contain a high load of contaminants that can infiltrate the soil and affect nearby water bodies [25]. Another significant effect is the generation of unpleasant odors, attributed to the decomposition of organic matter present in the waste. In this regard, [26] states that volatile compounds emitted during waste degradation can affect air quality and cause discomfort to the surrounding population; moreover, prolonged exposure to these compounds has repercussions on human health.

Soil contamination is another issue resulting from poor leachate management. According to [27], MSW leachate contains heavy metals and organic compounds that alter soil quality and reduce its capacity for plant growth. Inadequate collection—characterized by leachate leakage from compactor trucks—significantly contributes to this impact [31]. Another direct consequence of gas release from waste decomposition and the emission of suspended particles is atmospheric pollution. In this regard, [28] states that waste collection and transportation processes can contribute to the emission of particulate matter and greenhouse gases, which exacerbate the environmental and climate issues caused by MSW.

Given this context, it is imperative to improve the mechanisms for solid waste collection, treatment, and final disposal to mitigate their negative impacts. Strategies such as the implementation of sealed collection systems, proper leachate treatment, and optimized transportation can help minimize the adverse effects on the environment and public health [29]. Likewise, [30] states that the application of daily cover in landfills reduces the emission of volatile compounds responsible for unpleasant odors, as well as the proliferation of biological vectors such as rodents and insects.

E. Supply chain

The current supply chain flow for solid waste management in Bolívar begins with the collection of waste at its points of generation, followed by transportation to the shared area (emergency cells), where it is ultimately disposed of.

Figure 4 presents the MSW supply chain model, a basic linear model in which waste is collected at its point of generation, transported, and finally disposed of in emergency cells. Although functional, this approach presents environmental and operational limitations. As noted in [33], the collection stage is essential to ensuring the effectiveness of the entire supply chain in waste management, followed by transportation, which—through adequate modeling—allows for optimizing collection routes and frequencies, thereby significantly reducing operational costs and pollutant emissions [34].

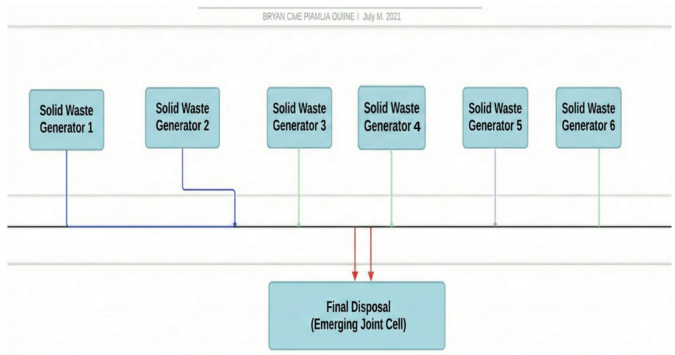

Fig. 4. Supply chain flow diagram.

In summary, the current supply chain model in the Bolívar canton reflects a waste management system focused primarily on final disposal, which is not sustainable in the long term. Therefore, the incorporation of practices based on the circular economy and the strengthening of collection and transportation infrastructure can help minimize environmental impacts and improve system efficiency [35]. Additionally, active community participation is key to ensuring the success of these initiatives [32].

F. Design of transfer stations

The study conducted by [36] highlights the importance of automation in waste treatment to improve process efficiency and reduce operational workload. In this context, the inclusion of a six-meter conveyor belt with adjustable speed represents a strategy that allows the process to adapt to different waste volumes, optimizing the time and effort required for sorting [37].

Previous research demonstrates that variability in conveyor belt speed is essential for improving performance and minimizing energy consumption in waste transfer stations [38]. Furthermore, the open design of the belt facilitates maintenance and constant visual inspection, contributing to equipment durability and preventing mechanical failures [39]. This system enables early detection of failures and the implementation of timely corrective measures, reducing downtime and improving overall process efficiency [40].

Automation in MSW management enhances the efficiency of material separation and classification, optimizing resource use and reducing final disposal in landfills. The implementation of a ground-level conveyor belt facilitates loading into the system.

This system disperses waste on the sorting belt and separates hazardous items—an approach that enhances both safety and efficiency. However, the use of mini-loaders to feed waste into the system could further increase efficiency. Thus, the combination of mechanical equipment and manual operation optimizes waste management in urban environments.

Transporting unsorted materials to a bidirectional conveyor belt and subsequently to the compaction box aligns with circular economy principles. Compacting waste into predetermined dimensions not only facilitates storage and transportation but also reduces the volume of waste to be managed. Reducing volume at the source minimizes logistical and environmental costs, which are essential for continuous process improvement. It is important to emphasize that implementing recycling strategies and proper waste disposal is crucial.

Consequently, the proposed stations are based on utilizing waste to generate income that will help reduce the existing economic deficit in the Bolívar GAD. Additionally, these plants will improve collection frequency and coverage, enabling additional routes, as the stations will be strategically located in Calceta and Quiroga, thereby shortening final disposal times.

Furthermore, Tables XI and XII show the potential revenues of the transfer stations for both organic and inorganic waste:

TABLE XI
REVENUES OF THE CALCETA TRANSFER STATION (C), WITH A TRANSFER STATION CAPACITY (CVR) OF 25 T/DAY

Waste type	**Quantity**	**USD/kg minimum**	**USD/kg maximum**	**USD/day minimum**	**USD/day maximum**
Paper and cardboard	3 900	0,05	0,1	195	390
Hard plastic	1 050	0,15	0,25	157,5	262,5
Soft plastic	1 050	0,05	0,1	52,5	105
Tetrapak	1 050	0,05	0,1	52,5	105
Glass	2 000	0,009	0,01	18	20
Metal	1 175	0,05	0,06	58,8	70,5
MO	14 375	0	0	0	0
Hazardous waste	400	0	0	0	0
Daily income				534,25	953
Monthly income				13 890,5	24 778
Annual income				167 220,25	298 289

TABLE XII
REVENUES OF THE QUIROGA–MEMBRILLO TRANSFER STATION (QM) WITH A QM TRANSFER STATION CAPACITY (CVR) OF 6 TONS/DAY

Waste type	**Quantity**	**USD/kg mín**	**USD/ kg máx**	**USD/ mín**	**USD/ máx**
Paper and cardboard	945	0,05	0,1	47,25	94,5
Hard plastic	226,8	0,15	0,25	34,02	56,7
Soft plastic	226,8	0,05	0,1	11,34	22,68
Tetrapak	226,8	0,05	0,1	11,34	22,68
Glass	453,6	0,009	0,01	4,1	4 536
Metal	232,2	0,05	0,06	11,6	13 932
MO	3051	0	0	0	0
Hazardous waste	37,8	0	0	0	0
Daily income				119,64	215,03
Monthly income				3 110,70	5 590,73
Annual income				37 448,07	67 303,76

Tables XI and XII show the revenues from the sorting processes at the C and QM transfer and sorting stations. These tables present the minimum and maximum revenues obtained from materials such as paper, cardboard, rigid plastic, soft plastic, and Tetrapak. Maximum and minimum revenues were considered due to price fluctuations of these materials. It is important to note that organic matter was not included in the analysis, as its price depends on the characteristics and quality of the compost; however, it could be used in community nurseries and other nurseries associated with the municipal GAD [37].

The use of recyclable solid waste represents a key strategy in sustainable urban waste management, as it not only reduces the amount of waste sent to landfills but also generates economic income from the sale of recovered materials. The prices of recyclable materials depend on factors such as global demand, material quality, and local waste management policies. This volatility was considered in the analysis by incorporating maximum and minimum estimates, providing a more realistic view of the economic impact of recycling in the locality.

The strategy for utilizing organic waste in community nurseries associated with the Bolívar GAD aligns with a circular economy approach, promoting efficient resource use and reducing management costs. Fig. 5 presents the supply chain diagram, including the treatment stage, as part of the proposal for solid waste management in the Bolívar canton [39].

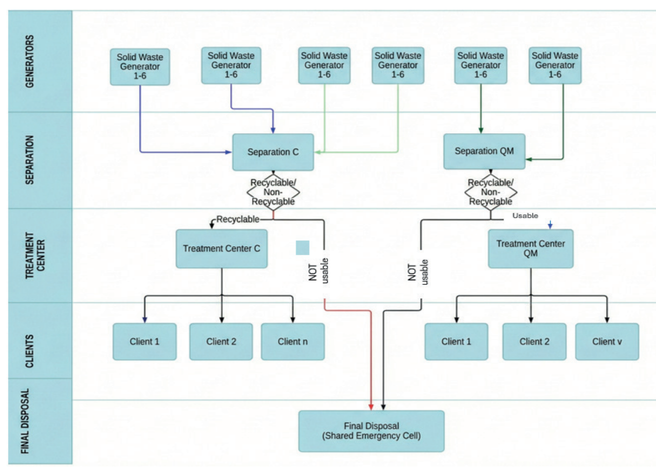

Fig. 5. Proposed flow diagram of the solid waste supply chain.

From this perspective, Table XIII presents a summary of the projected values associated with the solid waste separation and treatment service:

TABLE XIII
PROJECTION ASSOCIATED WITH THE SEPARATION AND TREATMENT SERVICE: (C), (QM)

Description	**Expense**	**Max income**	**Min income**	**Max difference**	**Min difference**
Annual budget allocation for the station (QM)	119 574,80	67 303,80	37 448,07	-52 271,00	-82 126,73
Annual station budget allocation (C)	219 175,20	298 289	167 220,25	79 113,80	-51 954,95

Total annual cost of waste separation service	-338 750	-	-	-	-
Annual income from transfer stations (QM+C)	-	365 592,80	204 668,32	-	-
Difference between annual expenses and income	-	-	-	26 842,80	-134 081,68
Difference between monthly expenses and income	-	-	-	2 236,9	-11 173,47

As shown in Table XIII, the total annual cost of the solid waste separation and treatment services is USD 338 750/year, while the maximum revenue from separation and treatment is USD 365 592,8/year, resulting in a difference of USD 26 842,8/year in favor of the latter. This value may increase after the ninth year of operation, since the investment recovery period is nine years.

Therefore, the difference between expenses and revenues from separation and treatment with minimum revenues is -USD 134 081,68/year, which represents a monthly capital loss of USD 11 173,47/month. It is important to note that the annual cost of the separation and treatment service will decrease in the tenth year of operation, as the investment is amortized over nine years. This means that in the tenth year, the total annual cost of the separation service will cover only the costs associated with the operation and maintenance of the transfer and separation stations [40].

The results obtained reflect the long-term economic feasibility of the solid waste separation and treatment service, especially after the ninth year of operation. The profitability of solid waste management systems depends on factors such as the initial investment, operating costs, and revenue sources. In this case, the positive difference of USD 26 842,8/year in the maximum-income scenario suggests a positive margin that may increase once the initial investment is fully recovered.

However, the minimum-income scenario reveals an annual loss of USD 134 081,68/year, which implies a monthly deficit of USD 11 173,47. Fluctuations in revenue may be due to variations in the demand for recycled materials and operating costs, making it necessary to implement strategies to optimize efficiency in waste separation and recovery.

It is important to consider that after the tenth year, operating costs will decrease significantly, as the initial investment will have been amortized. One of the key strategies for the sustainability of these systems is long-term financial planning, ensuring that operational revenues allow the operation of the transfer and sorting stations without dependence on external subsidies [36].

Improving efficiency in the collection and marketing of separated waste is also recommended, optimizing logistical routes and promoting citizen participation in source separation. Moreover, community involvement in source separation is crucial for improving the quality of recovered materials and, consequently, increasing system revenues.

Finally, it is evident that the generation of solid waste in the Bolívar canton is strongly influenced by cultural habits, with the following findings: 57 % of the waste generated corresponds to organic matter with high composting potential; rural waste collection coverage remains low; the economic deficit is associated with the current collection model and the lack of economic recovery actions linked to the integrated solid waste management flow proposed within the framework of the circular economy for Ecuador. Although the country has a high potential to scale differentiated actions in waste management.

G. Multicriteria Analysis

From the weighting of criteria and subcriteria, the decision matrix of alternatives was obtained:

TABLE XIV
DECISION MATRIX

Criterion (Weighting)	**Subcriterion (Weighting)**	**Score (0-10) Current system**	**Score (0-10) Proposed system**	**Justification of score**
Environmental (40 %)	Environmental impact (20 %)	1	9	The current system has a “critical” impact, while the proposed system significantly mitigates it.
	Utilization rate (20 %)	0	10	The current system does not recycle waste (0 %), while the proposed system aims for 51,5 %.
Economical (30 %)	Annual Operating Cost (15 %)	2	8	The proposed system ($170 967) is more economical to operate than the current one ($191 388).
	Income potencial (15 %)	0	10	The proposed system can generate $73 001 in annual revenue; the current system generates none.
Social (20 %)	Job Creation (10 %)	3	9	The new model creates jobs in sorting and management, beyond collection.
	Public Health (10 %)	2	9	The current model creates hotspots for infection; the proposed model improves sanitary conditions.
Technique (10 %)	System Efficiency (5 %)	3	8	The proposed model optimizes routes and processes, improving overall efficiency.
	Operational Complexity (5 %)	9	4	The current system is simpler to operate, while the proposed system requires more management and logistics.

On the other hand, the high weightings reflect an analysis of the conditions that favor the proposed models over the current ones. Likewise, this type of data provides valuable information for facility location and urban governance, while also highlighting areas for future research. It is important to note that the application of multicriteria analysis leads to an optimized selection of final waste disposal sites, as well as an improved MSW management system in urban and peri-urban areas.

IV. CONCLUSION AND RECOMMENDATION

The study on solid waste generation in the Bolívar canton reveals an average per capita production (PPC) of 0,72 kg/inhabitant/day, while the residential sector generates 0,36 kg/inhabitant/day. Organic waste accounts for 57 % of the total waste generated in the canton, followed by paper and cardboard (17 %), PET plastic (13 %), glass (8 %), and metals (5 %). Hazardous waste represents 1 % of the total. The collection system is door-to-door, but coverage varies among parishes. Calceta has a coverage rate of 69 %, Quiroga 50 %, and Membrillo only 22 %. Additionally, the monthly fee per household for the Integrated Solid Waste Management (GIRS) service amounts to USD 6,60, based on the total cost of the service. The total annual operating cost is USD 696 106.60, with an annual deficit of USD 504 687.13.

The current supply chain flow for solid waste management in the Bolívar canton follows a basic linear model, in which waste is collected directly at its point of generation, transported, and finally disposed of in emergency cells. Although functional, this approach lacks strategies for waste reduction, reuse, or recycling, which limits its long-term sustainability and efficiency. The implementation of a more circular management model will optimize waste management, minimize environmental impacts, and improve the use of available resources.

The implementation of transfer stations for the management of organic and inorganic waste optimizes the urban solid waste (MSW) management process by reducing costs, decreasing the number of trips—and therefore fuel, vehicle maintenance, and labor costs—improving efficiency, shortening transportation times from collection vehicles to treatment or final disposal facilities, enabling more collection routes, and enhancing overall service efficiency.

The transfer stations are equipped to sort waste, separating recyclable materials such as paper, cardboard, plastic, and glass. This facilitates their subsequent processing and recovery. These wastes are compacted at the transfer stations, reducing their volume and optimizing landfill space.

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