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J. Hidalgo-Crespo, Pasiano Rivas-García, Ever Efraín García-Balandrán, Alonso Albalate-Ramírez, Samuel Quintero-Herrera, et al.. Validating Circular End-of-Life Strategies for Domestic Post-Consumer Materials in the Latin American Region: A Life Cycle Assessment Approach. *Environments*, 2024, 11 (11), pp.228. 10.3390/environments11110228. hal-04798329

HAL Id: hal-04798329

<https://hal.science/hal-04798329v1>

Submitted on 22 Nov 2024

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Article

Validating Circular End-of-Life Strategies for Domestic Post-Consumer Materials in the Latin American Region: A Life Cycle Assessment Approach

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Citation: Hidalgo-Crespo, J.; Rivas-García, P.; García-Balandrán, E.E.; Albalate-Ramírez, A.; Quintero-Herrera, S.; Velastegui-Montoya, A.; Amaya Rivas, J.L.; Soto, M. Validating Circular End-of-Life Strategies for Domestic Post-Consumer Materials in the Latin American Region: A Life Cycle Assessment Approach. *Environments* **2024**, *11*, 228. <https://doi.org/10.3390/environments11110228>

Academic Editor: Dimitrios Komilis

Received: 21 August 2024

Revised: 8 October 2024

Accepted: 14 October 2024

Published: 22 October 2024



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Abstract: This study examines the domestic solid waste management system in the LATAM region, using the city of Guayaquil in Ecuador as a case study. Through the life cycle assessment (LCA) methodology, the study compares domestic and external recycling processes, evaluating their effects on global warming potential, fossil resource scarcity, and terrestrial ecotoxicity. The results reveal that increasing recycling rates significantly reduces environmental impacts, with domestic recycling offering slightly higher environmental benefits than external options. A demographic analysis using machine learning techniques identifies distinct patterns of waste generation across different population clusters, highlighting the need for tailored waste management strategies. The study also emphasizes the importance of accurate local data and the integration of recycling initiatives with market realities, particularly in the light of policies mandating recycled content in products like PET bottles. A sensitivity analysis of the waste recovery indicator (WRI) demonstrates the potential for substantial environmental and economic benefits with higher recycling rates. The findings suggest that, to advance towards a circular economy, Latin American cities like Guayaquil must enhance their recycling infrastructure, refine waste management policies, and focus on demographic-specific strategies. This research contributes to the broader understanding of sustainable waste management in developing regions, offering insights for future policy and infrastructure development.

Keywords: waste recovery; domestic; life cycle assessment; clustering and correlations functions; recycling scenarios; paper and cardboard; plastic; glass; metal; textile

1. Introduction

The global environmental crisis is characterized by the overproduction of waste, notably household waste, spurred by consumer behavior and rapid urban development [1,2]. Inadequate waste management contributes to the pollution of air, water, and soil [3]. Municipal solid waste management (MSWM) systems in developing nations often exhibit inefficiencies due to insufficient administrative and financial frameworks, regulatory structures, infrastructure, and human resources [4,5]. Moreover, around one billion urban residents, particularly in low- and middle-income countries in the Latin American (LATAM) region, lack access to consistent waste management services [6].

Solid waste in urban regions is generally categorized into two primary types: domestic (municipal solid waste, MSW) and commercial–industrial waste. Like other developing nations, countries in the LATAM region face challenges with illegal dumping, open burning of waste, and unregulated disposal practices [2]. While sanitary landfilling is often the sole method of waste treatment and disposal in many LATAM countries, deficiencies in waste collection systems persist, particularly in the more remote urban areas.

Numerous countries recognize the severity of waste management issues and have implemented policies aimed at reducing MSW generation through the principles of the 3R or 4R (reduce, reuse, recycle, and recover) [7]. Scholarly sources indicate that waste management strategies within a circular economy (CE) primarily involve reducing the consumption of virgin raw materials, reusing processed materials, and recycling waste [8]. Discussions on CE approaches to waste management, particularly in the LATAM region, are prevalent in recent academic research. For modern societies to achieve sustainability, the recycling of MSW is crucial, necessitating a directional shift in MSWM systems to enhance markets and recycling industries [9].

Several strategies exist for managing household recyclable materials, including landfilling, incineration, and recycling into new products [4]. Both landfilling and recycling have their environmental advantages and drawbacks. Landfilling can result in methane emissions, land occupation, and the contamination of soil, groundwater, rivers, and oceans. On the other hand, recycling helps decrease the demand for primary materials but involves transportation logistics. Nevertheless, recycling is not universally applicable, particularly for materials composed of multiple types of plastics or combinations of plastics and metals (disagreeing with the sixth principle of green engineering).

All waste management processes entail environmental impacts, making it challenging to discern the most beneficial option. Life cycle assessment (LCA) offers a method to evaluate and compare the environmental effects of various processes by quantifying the array of impacts a process may have on the environment [5]. LCA studies have demonstrated that transportation, sorting, and disposal processes significantly contribute to the environmental footprint of household recyclable waste. These impacts can be mitigated through selective sorting at the point of generation [9]. The effective separation of recyclable waste is crucial to maintaining the quality of the recycled output.

Recycling substantially decreases greenhouse gas emissions and energy consumption while conserving landfill space. The extent of material recycling is influenced by various factors, including income levels, the presence of local and national markets, the demand for secondary raw materials, the intensity of financial and regulatory government interventions, the cost of virgin raw materials, international trade in secondary raw materials, and applicable treaties [9]. Therefore, the effectiveness and sustainability of the recycling chain require efficient coordination by municipal stakeholders [10].

Recycling materials such as newspaper, cardboard, mixed paper, glass bottles and jars, aluminum cans, tin-plated steel cans, and plastic bottles from household solid waste generally consumes less energy and results in lower environmental impacts compared to landfilling or incineration, even when considering the potential energy recovery from these disposal methods. This advantage persists across various environmental impact categories, including global warming potential, acidification, eutrophication, human toxicity, and ecological toxicity [11]. Additionally, Botello-Álvarez et al. [4] employed LCA to assess

the environmental impact of recycling valuable solid waste in Mexican systems, revealing beneficial outcomes.

Until recently, quantitative data on waste generation and management in cities within developing regions of LATAM have been limited and often unreliable, particularly concerning recycling rates [12]. The collection of household waste presents a stochastic challenge, as waste quantities fluctuate considerably based on multiple factors, including population density, lifestyle, dietary habits, seasonal changes, and patterns of movement and migration. Accurate data on the generation and characteristics of recyclable waste are crucial for developing effective management strategies [13]. Such information aids in determining the ideal locations for waste treatment or recovery facilities [14,15], optimizing waste collection routes [14,16], and planning for space allocation in recycling systems.

As logistics pose a significant challenge to quantifying recyclable materials, the use of Geographical Information Systems (GIS) is essential. GISs enable the capture and analysis of location-based intelligence regarding the distribution and value of recyclable resources and their collection systems, thereby providing the community with comprehensive, precise, and accessible information [17]. GISs represent advanced modern technology designed to capture, store, manipulate, analyze, and display data, typically organized into thematic layers on digital maps [18]. GISs have been effectively employed in various applications, including the management of recycling drop-off centers [19] and the estimation of solid waste generation through the analysis of local demographic and socioeconomic data [20].

Based on the analysis of waste management inefficiencies in the LATAM region and the integration of recycling strategies, this study aims to explore the following research question: how can Geographic Information Systems (GISs) and life cycle assessment (LCA) frameworks optimize municipal solid waste recycling systems in the LATAM region, particularly in terms of reducing environmental impacts and enhancing resource recovery? To address this, we hypothesize that (1) the implementation of GISs for mapping and analyzing recyclable material distribution will significantly improve the efficiency of collection routes, resulting in reduced greenhouse gas emissions and energy consumption; and (2) the application of LCA to various recycling scenarios will demonstrate that selective sorting at the point of waste generation enhances material recovery rates and lowers overall environmental impacts compared to traditional landfilling methods. These hypotheses aim to validate the potential of advanced technologies in transforming waste management practices in developing regions.

The innovation of this study is found in its development of a holistic and detailed framework that integrates validated mass and energy balances to assess different recycling scenarios in the LATAM region. This framework accounts for fluctuations in waste generation linked to socio-demographic factors at the initial collection phase and facilitates an extensive examination of impacts across the entire waste management system by connecting with downstream processes such as treatment, recovery, and disposal. The primary focus of this research is on domestic recyclable waste, characterized by a diverse mix of recoverable materials requiring effective separation, collection, and treatment strategies. The framework delineates five significant categories of segregated recyclable materials—plastics, metals, glass, fabrics, and paper/cardboard—with further subdivisions in most categories and incorporates assorted technologies pertinent to the treatment of each waste stream. The goals of this research include (a) establishing a comprehensive framework with validated mass and energy balances for multiple recycling scenarios, (b) verifying these scenarios using life cycle assessment, and (c) applying the model to waste data from the Grand Guayaquil Metropolis to derive policy recommendations based on the outcomes of the scenario analysis.

In the following, Section 2 will demonstrate information on the materials and methods used in the development of this research. The results are presented in Section 3, and the study's discussion, and theoretical and practical implications together with its limitations are presented in Section 4. Finally, Section 5 summarizes the research main points.

2. Materials and Methods

Figure 1 shows in detail all the sections into which the materials and methods section of this work is divided by means of a flow chart.

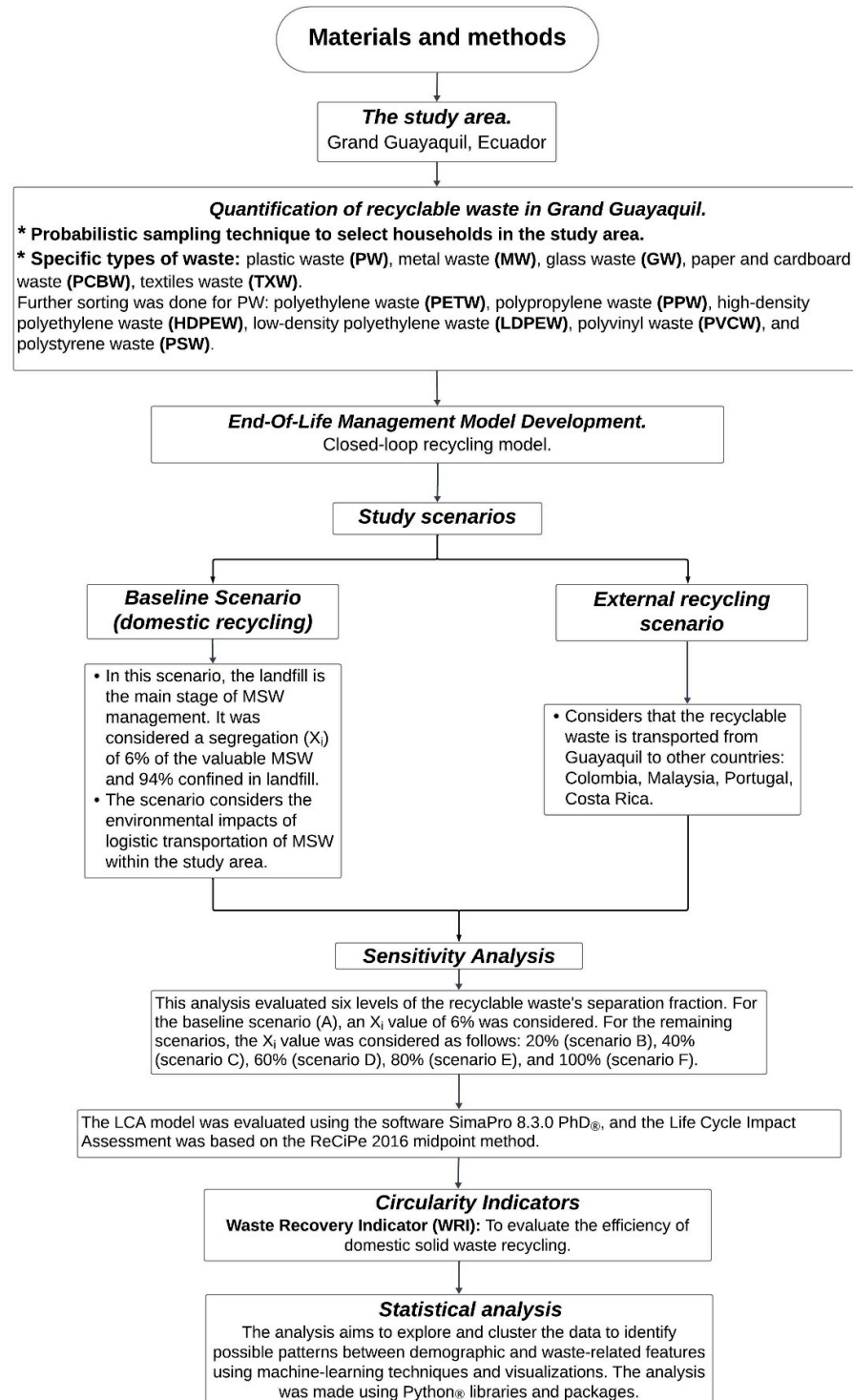


Figure 1. Flowchart for the materials and methods section.

2.1. The Study Area

Ecuador's population stands at roughly 17 million individuals. The World International Bank [21] reported that Ecuador has attained a Gross Domestic Product per capita (GDPpc) of USD 5920. The country's administrative framework comprises the Central Government, 24 provincial governments, 221 municipalities, and 1149 parishes, with municipal administrations holding exclusive jurisdiction [22].

In the country, solid waste management is administered by 183 municipalities through dedicated units or departments, 22 via Joint Public Enterprises (involving collaboration among two or more municipalities), 10 through Public Companies, and 5 within the Commonwealth framework. Data from the 2012 Census of Environmental Information on the Autonomous Decentralized Municipal Governments reveal that household waste primarily consists of 63% organic materials, 12% plastics, 3% glass, 2% metal, 1% wood, 5% paper, 5% cardboard, and 1% scrap metal.

Solid waste management is overseen by 183 municipalities via specific units or departments, 22 through Joint Public Enterprises (collaborative entities involving two or more municipalities), 10 by Public Companies, and 5 within the Commonwealth. Based on the 2012 Census of Environmental Information for Autonomous Decentralized Municipal Governments, the composition of household waste predominantly includes 63% organic waste, 12% plastics, 3% glass, 2% metal, 1% wood, 5% paper, 5% cardboard, and 1% scrap metal.

According to Ecuador's National Program for the Integral Management of Solid Waste (PNGISD), 25% of the daily waste generated has recycling potential. Nonetheless, those involved in recycling recover only 5% of this potentially reusable waste. In 2016, approximately 41% of Ecuadorian households engaged in waste sorting, meaning four out of ten households participated in this practice. Nationally, the most commonly sorted materials are plastic (34%), followed by organic waste, paper, and cardboard (each 25%), and glass (15%).

Within Ecuador, the Grand Guayaquil area encompasses the city of Guayaquil, the provincial capital of Guayas, and is situated on the Pacific Ocean coast in Ecuador's coastal region. Additionally, it includes parts of three neighboring cities—Daule, Samborondón, and Durán—where the predominant economic activities are closely tied to Guayaquil. According to prior research [23], the area is defined by 91 polygons, five identified as extensions.

2.2. Quantification of Recyclable Waste in Grand Guayaquil

One previous study involving the authors had as its objective the prediction of the total recyclable waste produced for the area of Grand Guayaquil [23]. First, the quantification of recyclable waste involved a direct approach employing a probabilistic sampling technique to select households in the study area. Households were strategically chosen to maintain uniform spatial distribution throughout the urban periphery. Each household was instructed to separate and store recyclable waste (plastic, paper and cardboard, metal, glass, and fabric) in designated bags. The collection process spanned four weeks, during which students collected, sorted, and weighed the waste. The sorted waste was categorized into specific types: plastic waste (PW), metal waste (MW), glass waste (GW), paper and cardboard waste (PCBW), textile waste (TXW), and detailed records were maintained for each type of recyclable material. In addition, further sorting was carried out for plastic waste, also obtaining data for polyethylene waste (PETW), polypropylene waste (PPW), high-density polyethylene waste (HDPEW), low-density polyethylene waste (LDPEW), polyvinyl waste (PVCW), and polystyrene waste (PSW). Data from the collected waste were then analyzed using Geographic Information Systems (GISs) to predict recyclable household waste quantities and spatial distribution.

For this work, the general quantities predicted for GW, MW, PCBW, PW, and TXW will be used, as well as the subdivisions for plastics (PETW, PPW, HDPEW, LDPEW, and PSW) [23]. The subdivisions of metal, paper, cardboard, and textile waste are performed with the help of literature, as shown in the following paragraphs. Table 1 shows their subdivisions and the percentages that will be used for the case study analysis of this research.

Table 1. Subdivision of paper and cardboard waste, glass waste, textile waste, and metal waste.

Metal Waste		Paper and Cardboard Waste	
Type	Percentage ¹	Type	Percentage ¹
Tin-plated steel	54.00	Magazines and advertising	19.97%
Stainless steel	15.00	Newsprint	16.09
Aluminum	24.00	Office/administrative paper	9.97
Other metals	8.00	Books	0.69
Non-metals	1.00	Cardboard and paperboard	22.56
		Tissue paper	14.97
		Other paper	15.75
Textile Waste		Glass Waste	
Type	Percentage ¹	Type	Percentage ¹
Clothing	48.00	Packaging container	85.71
Household textiles	22.00	Table and kitchenware	9.52
Other textiles	30.00	Other/special	4.76

¹ Percentages are in terms of mass.

For the case of the metal fraction in domestic waste, one primary waste characterization performed in Denmark divided household waste into 48 fractions, where metal waste represented 2.83% of the total waste (18.73% for aluminum foil, 31.22% for metal-like foil, 6.71% for steel metal containers, and 41.34% for other metals) [24]. Another more accurate study performed in Finland at the Helsinki Metropolitan Area found that, in total, the composition of the metal fraction of solid domestic waste was 54% tin-plated steel, 15% stainless steel, 24% aluminum, 8% other metals, and 1% non-metals [25].

For the case of the paper and cardboard fraction in domestic waste, one study performed in Denmark showed the source-segregated types of this waste having a total of seven: magazines and advertising, newsprint, office/administrative paper, books, tissue paper, other paper, cardboard, and paperboard [26]. According to [27], the mass distribution of the paper and cardboard fraction in Danish household waste represents 23.18%, with magazines and advertising representing 19.97%, newsprint 16.09%, office/administrative paper 9.97%, books 0.69%, cardboard and paperboard 22.56%, tissue paper 14.97%, and other paper such as dirty paper and cardboard 15.75%.

For the case of the textile fraction in domestic waste, the EU Nomenclature Chapters 61–63 subdivided this fraction into three sub-fractions, namely, clothing, household textiles, and other textiles, giving a clear and constant understanding of what the fraction consists of [28]. According to [29], the mass distribution of the textile fraction in Danish household waste represents 2.8% of the total waste being clothing, the highest at 48%, followed by household textiles and other textiles at 22% and 30%, respectively.

For the case of the glass fraction in domestic waste, a subdivision has been developed by [26] with three types, namely, glass packaging container, kitchen and tableware glass, and other/special glass, with three different color variations: clear, brown, and green. According to [24], the mass distribution of the glass fraction in Danish household waste represents 2.1%, with glass packaging containers at 85.71%, table and kitchenware glass at 9.52%, and other/special glass at 4.76%.

2.3. End-of-Life Management Model Development

Figure 2 shows a recycling model for recyclable MSW focused on closed- and open-loop recycling. In the closed-loop recycling, the inherent properties of the recycled material do not differ significantly from those of virgin material. Therefore, recycled material can substitute for virgin material and be used in the same type of products [30–33]. The proposal model aims to provide a general description of a typical recycling system focusing on closed-loop recycling.

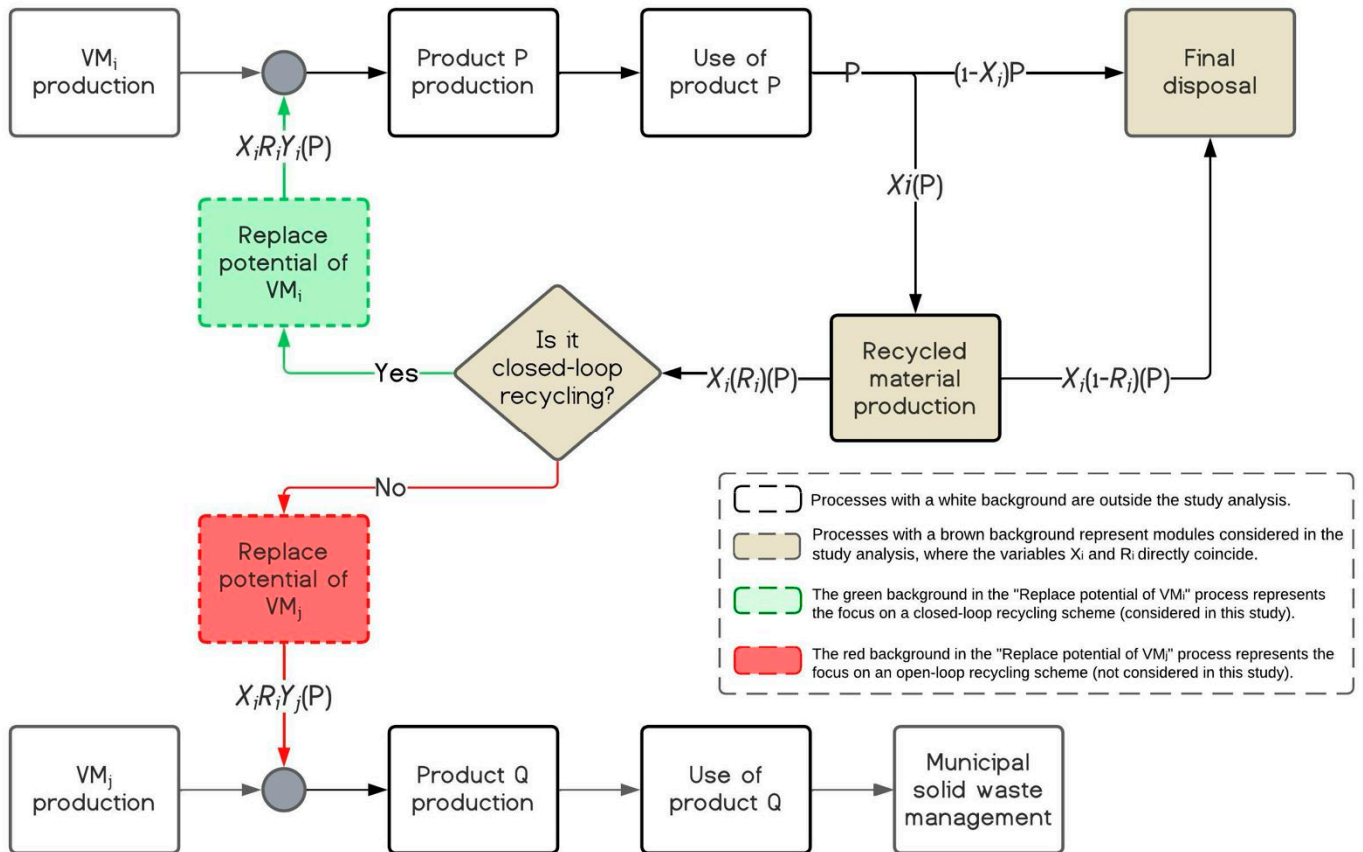


Figure 2. Recycling model diagram. Note: X_i : Fraction of waste separation. R_i : Efficiency of recycled material production. Y_i : Efficiency of virgin material substitution. VM: Virgin material. The sub-index denotes the recycling model, i for closed loop or j for open loop.

The variable X_i represents the fraction of waste that can be effectively segregated in recycling plants for subsequent valorization. R_i denotes the efficiency in producing recycled material, i.e., the conversion of separated waste into useful recycled material. Finally, Y_i expresses the efficiency in substituting virgin material, that is, the proportion in which recycled material can effectively replace virgin material in producing new products. For example, the average value of the variable Y_i for PET is approximately 0.81, which indicates that PET has a substitution efficiency of 81% for virgin PET (flakes, pellets, or granules).

Table 2 shows the results of an extensive literature review in which the variables X_i , R_i , and Y_i were defined for various fractions of valuable waste. This model focuses on closed-loop recycling. The fractions are grouped into five categories: plastics, paper and cardboard, glass, metals, and fabrics (textiles).

Table 2. Parameters in the recycling model (closed loop).

Valuable Solid Waste (VSW)	X _i : Fraction of VSW Separation	R _i : Efficiency of Recycled Material Production	Y _i : Efficiency of Virgin Material (VM) Substitution	Virgin Material That Is Substituted
Copper	0.90 ^k	0.80 ^a	0.85 ^a	Primary copper
Nickel	0.82 ^a	0.57 ^a	0.42 ^o	Primary nickel
Steel	0.79 ⁱ	0.85 ⁱ	0.97 ⁱ	Crude steel
Aluminum	0.95 ^j	1 ^h	0.9 ^h	Primary aluminum
Paper and cardboard	0.91 ^m	0.89 ^b	0.83 ^b	Virgin sulfur pulp
PET (polyethylene terephthalate)	0.65 ^g	0.90 ^f	0.81 ^f	Flakes/pellets/granules from virgin material
PVC (polyvinyl chloride)	0.94 ^c	0.80 ^d	0.83 ^e	Flakes/pellets/granules from virgin material
HDPE (high-density polyethylene)	0.84 ^c	0.84 ^d	0.81 ^b	Flakes/pellets/granules from virgin material
LDPE (low-density polyethylene)	0.53 ⁿ	0.76 ^l	0.78 ^l	Flakes/pellets/granules from virgin material
PP (polypropylene)	0.86 ^c	0.68 ^c	0.87 ^d	Flakes/pellets/granules from virgin material
PS (polystyrene)	0.72 ^c	0.66 ^d	0.77 ^g	Flakes/pellets/granules from virgin material
Glass	0.90 ^p	0.74 ^q	0.80 ^q	Virgin glass
Fabrics (textiles)	0.75 ^r	0.80 ^s	0.50 ^s	Virgin textiles

Note. ^a -> [34]. ^b -> [35]. ^c -> [36]. ^d -> [37]. ^e -> [38]. ^f -> [39]. ^g -> [40]. ^h -> [41]. ⁱ -> [42]. ^j -> [43]. ^k -> [44]. ^l -> [45]. ^m -> [46]. ⁿ -> [47]. ^o -> [48]. ^p -> [49]. ^q -> [50]. ^r -> [51]. ^s -> [52].

2.4. Study Scenarios

In this section, the study scenarios considered in this research are presented, which correspond to two distinct cases: the “baseline scenario (domestic recycling)” and the “external recycling scenario”. Each scenario will be explained in detail below, outlining their specific characteristics and the conditions under which they were developed to assess their impact and feasibility within the study’s context.

2.4.1. Baseline Scenario (Domestic Recycling)

Following previous works in the study area (Grand Guayaquil, Ecuador), the recycling process can occur formally and informally. In the formal section, the MSW is collected by collector trucks at the curbsides of the city, generally mixed with non-recyclables and organic materials from households. Later, sorting occurs at the landfill site by hand or by automatic machinery, the last one being the most efficient method. After, the valuable fractions of MSW (with recycling potential) are sent to a waste transfer station that can be in the same landfill location or outside.

Finally, the valuable waste fractions are transported to the different recycling plants in the city. For informal recycling, curbside collection is achieved by informal waste pickers (IWPs) or curbside recycling associations. People involved in this work travel to different areas of every city and collect recyclable waste by hand using trolleys, hand-carriages, bicycles, and vehicles. This collected waste is then given to different waste transfer stations in the city that serve as accumulators and prepare the waste to be sent to the recycling facilities [4,23,33].

In the baseline scenario, the landfill is the main stage of MSWM. It was considered an earlier segregation (X_i) of 6% of the valuable MSW (fractions with recycling potential). The waste confined in the landfill is considered to be 94% of the MSW generated in homes, plus the mass loss in the recycling process due to the recycling efficiency of each material (Table 2).

In Figure 3, the system boundaries for the baseline scenario evaluation are outlined with a dashed line. The functional unit was recycling 1 ton of valuable MSW fractions. This scenario aims to assess the environmental impact of the recycling process of the valuable domestic solid waste fractions generated in any study area. The scenario considers the environmental impacts of logistic transportation within the country through all stages of the solid waste recycling process. The scope of the study excludes the construction of civil infrastructure and the manufacture of transportation trucks and other auxiliary and secondary transportation.

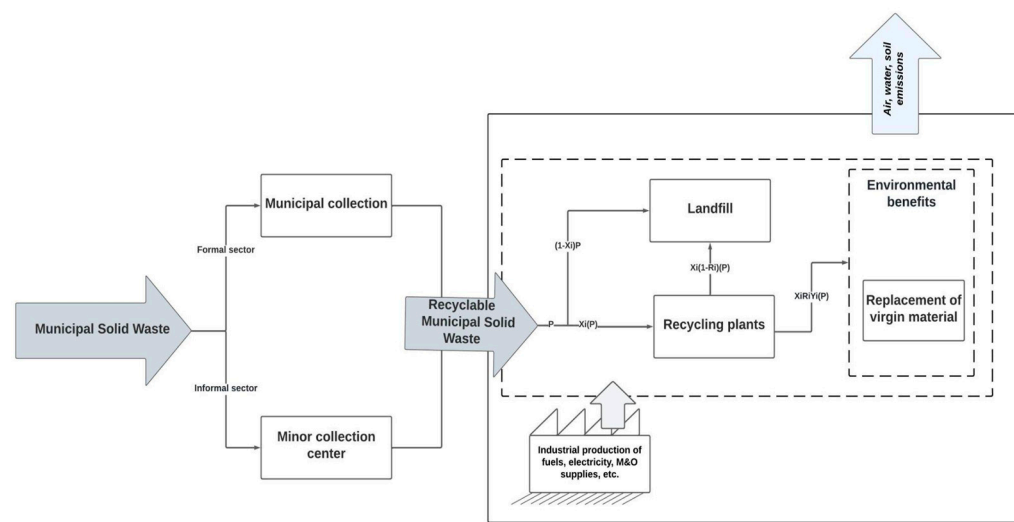


Figure 3. System boundary diagram of municipal solid waste recycling in Grand Guayaquil, Ecuador. Note: X_i : Fraction of waste separation. R_i : Efficiency of recycled material production. Y_i : Efficiency of virgin material substitution. P : Product P .

The environmental burdens generated in the transport activities and all the secondary data are evaluated using the EcoInvent v3.2 database. The landfilling process simulation is conducted using EaseTech,

EaseTech (Environmental Assessment System for Environmental Technologies) developed by DTU Environment and DTU Compute (Technical University of Denmark) which considers all necessary operational activities for MSW disposal in the sanitary landfill. The input data required to initiate the FDS model include the quantity of waste entering the site, the fractions of each waste category, and the physicochemical and bromatological characterization of the confined waste.

For the environmental assessment of domestic transport (within the city and other trans-city), a heavy-duty truck with a capacity of >32 metric tons was considered. The transportation distances between different points in the recycling process are shown in Table 3. At Point 1 (recycling plants), those plants within Guayaquil that function as collection and sorting centers for different recyclable waste were considered. Fibras Nacionales, S.A. was considered the starting point for the plastic, paper and cardboard, metals, and textiles fractions, while the EcoPrioridad plant was the starting point for glass. Point 2 considers Ecuador's principal production plants, where each recyclable waste fraction produces new materials (substituting virgin raw materials). Finally, Point 3 was established as the Las Iguanas sanitary landfill (SL), located northwest of Guayaquil, the city's leading final disposal site (FDS).

Table 3. Distances considered for domestic transportation of recyclable waste in Ecuador—baseline scenario (domestic recycling).

Recyclable Waste	Recycling Plant (Point 1)	Production Plant (Point 2)	Sanitary Landfill (Point 3)	Total Distance (km)
Plastics		Reciplásticos S.A. Daule, 7.5 km, Vía a Daule, Guayaquil, Ecuador		13.30
Paper and cardboard	Fibras Nacionales S.A. 7.5 km, vía Daule, Guayaquil, Ecuador	Papelera Nacional S.A. Cnel. Marcelino Maridueña, Ecuador		75.60
Metals		FUNDAMETZ S.A. Planta Pascuales. W3P5+7MW, Guayaquil, Ecuador	Las Iguanas W28W+P7M, Calle 27 NO, Guayaquil, Ecuador.	16.20
Fabrics (textiles)		Delltex S.A. Juan Montalvo, Quito 170157, Ecuador		426.40
Glass	Ecoprioridad Mz-50 solar 10, Guayaquil, Ecuador	Vitrum S.A. Vicente Duque 25, Quito 170310, Ecuador		434.40

The LCA model is developed using the software SimaPro v.9.5.0.2, PRé Sustainability B.V., Amersfoort, Utrecht, Netherlands and the Life Cycle Impact Assessment was based on the ReCiPe 2016 midpoint method [53]. The impact categories considered in this analysis were Climate Change (CC), Fossil Resource Scarcity (FRS), and Terrestrial Ecotoxicity (TE).

2.4.2. External Recycling Scenario

The external scenario considers that the recyclable waste is transported from Guayaquil to other countries. For the export of different recyclable waste, the paper also shows the leading countries of export for the different types of waste available in this study for the case of Ecuador, as shown in Table 4.

External transportation (ET) accounts for the distances involved in transporting each fraction of recyclable waste from Point 1 (recycling plants in Guayaquil, Ecuador) to Point 2 (Table 5). For the fractions of plastic, metal, and textile waste, Point 2 is considered the Guayaquil seaport, Point 3 the seaport of the destination country, and Point 4 (final point) the production plants in the destination country. For the paper, cardboard, and glass fractions, Point 2 is the final point, as only land transportation to production plants in Colombia is considered.

The points considered for each recyclable waste fraction and their respective total distances are shown in Table 5. The Google Maps geographic application was used as a tool for distance evaluation. A heavy-duty truck with a capacity of over 32 metric tons was considered for land transportation and a cargo ship with a capacity of 8500 TEU was used for sea transportation.

The considerations in aims and scope, inventory data, and environmental evaluation approach are the same as in domestic recycling scenario.

Table 4. Destination countries for Ecuador’s recyclable waste exports.

Type of Waste	Fraction (HS6-Digit)	Quantity (Tons/Year)	Percentages *
Plastic	Ethylene (391,510)	430.32	100.00
	Peru	189.00	43.93
	Malaysia	190.00	44.15
	Vietnam	50.00	11.62
	Dominican Republic	1.32	0.31
	Vinyl (391,530)	37.82	100.00
	USA	37.82	100.00
	Other Plastics (391,590)	2849.23	100.00
	Chile	940.48	33.00
	Brazil	829.04	29.10
	USA	337.59	11.85
	Malaysia	534.85	18.77
	Vietnam	165.63	5.81
Paper and Cardboard	Paper or Paperboard	8.26	100.00
	Colombia	8.26	100.00
	Other Paper or Paperboard	1821.04	100.00
	Colombia	1399.19	76.83
	Mexico	207.07	11.39
	El Salvador	121.37	6.66
	India	93.41	5.13
	Unbleached Kraft Paper (470,710)	1963.30	100.00
Colombia	1876.35	95.57	
Thailand	86.95	4.43	
Glass	Cullet and Other Glass Waste Scrap (700,100)	330.00	100.00
	Colombia	330.00	100.00
Metal	Stainless Steel Waste and Scrap (720,421)	2833.05	100.00
	India	974.30	34.39
	Netherlands	963.74	34.02
	USA	352.74	12.45
	Spain	217.58	7.68
	Panama	152.46	5.38
	Waste and Scrap of Alloy Steel (720,429)	330.37	100
	European Union	131.60	39.83
	Malaysia	67.17	20.33
	Spain	49.67	15.03
	Netherlands	81.93	24.80
	Waste and Scrap of Copper or Copper Alloy (720,429)	11,426.50	100
	China	5967.03	49.86
	Korea Republic	2540.92	22.24
	Brazil	1895.14	16.59
	Malaysia	271.52	2.38
	Spain	177.57	1.55
Zinc Waste and Scrap (790,200)	43.39	100	
India	43.49	100	
Textile	Waste of Synthetic Fiber (550,510)	1.02	100
	Costa Rica	1.02	100

* Percentages are in terms of mass.

Table 5. Distances considered for external transportation of recyclable waste from Ecuador to other countries.

Recyclable Waste	Recycling Domestic Plant (Point 1)	Production Plant or Seaport (Point 2)	Foreign Seaport (Point 3)	Production Plant (Point 4)	Total Distance (km)
Plastics		Puerto Marítimo de Guayaquil. 090112 Guayaquil, Ecuador	Port Klang Westports, Malaysia. Pulau Indah Highway, 42009 Port Klang, Selangor, Malaysia	Petronas Chemicals Ammonia Sdn. Bhd., 24300 Kerteh, Terengganu, Malaysian. Bhd., 24300 Kerteh, Terengganu, Malaysia	20,266
Paper and cardboard	Fibras Nacionales S.A. 7.5 km, vía Daule, Guayaquil, Ecuador	UNIBOL S.A.S., AUTOPISTA FRENTE ANTIGUO Aeropuerto, Soledad, Atlántico, Colombia			2240
Metals		Puerto Marítimo de Guayaquil. 090112 Guayaquil, Ecuador	European Union. Port of Sines, Av. Vasco da Gama, 7520-101 Sines, Portugal	Siderurgia Nacional R. Independência Nacional 10, 2840-996 Aldeia de Paio Pires, Seixal, Portugal	9446
Fabrics (textiles)		Puerto Marítimo de Guayaquil. 090112 Guayaquil, Ecuador	Puerto Caldera. Caldera, Provincia de Puntarenas, Espíritu Santo, Costa Rica	IKOR Industries. City of Puntarenas in the Province of Puntarenas, Costa Rica	1241
Glass	Ecoprioridad. Mz-50 solar 10, Guayaquil, Ecuador	Tecnoglass S.A.S., AVENIDA CIRCUNVALAR A 100 MTS DE LA, Via 40, Barranquilla, Atlántico, Colombia			2260

2.5. Sensitivity Analysis

A sensitivity analysis was conducted considering both the internal and external recycling scenarios. This analysis evaluated six levels of the recyclable waste's separation or segregation fraction (X_i , Figure 1). For the baseline scenario (A), an X_i value of 6% was considered; this separation percentage is the current average for the case study Grand Guayaquil. For the remaining scenarios, the X_i value was considered as follows: 20% (scenario B), 40% (scenario C), 60% (scenario D), 80% (scenario E), and 100% (scenario F). The main objective of the sensitivity analysis is to assess the environmental impact of increasing the recycling rate both locally (internal scenario) and by sending the valuable waste to other countries (external scenario).

2.6. Circularity Indicators

In a circular economy context, circularity indicators are crucial for assessing and monitoring the extent to which economic activities align with circular principles. These indicators provide quantitative measures to evaluate the efficiency of resource use, the effectiveness of waste reduction strategies, and the overall sustainability of products, processes, and systems. It is essential to have robust indicators that track progress, identify

areas for improvement, and guide decision making at various levels, from individual businesses to national policies [54].

A key circularity indicator was selected to evaluate the efficiency of domestic solid waste recycling: the waste recovery indicator (WRI, Equation (1)). This indicator represents the ratio of recovered waste (R, subindex) to the total generated municipal solid waste (MSW) within a specific period, measured by the proportion of MSW successfully recovered through recycling, composting, or other recovery processes (P, subindex). The WRI effectively reflects the efficiency of waste management systems in diverting waste from landfills [55]. This metric is essential for assessing progress towards a circular economy, as it quantifies the extent to which generated waste is reintegrated into the production cycle rather than being disposed of. Overall, the WRI provides a comprehensive evaluation of both waste generation and recovery, allowing for a thorough assessment of the sustainability and circularity of waste management practices in the studied regions [56].

$$WRI = \frac{MSW_R}{MSW_P} \quad (1)$$

2.7. Statistical Analysis

Data collected to assess the amount of recoverable domestic solid waste fractions per family in the Grand Guayaquil encompass demographic information, waste generation, and questions on various aspects of waste and recycling. These aspects range from knowledge and recycling practices at home to potential policies and programs to improve plastic waste management.

The analysis aims to explore and cluster the data to identify possible patterns between demographic and waste-related features using machine learning techniques and visualizations. The data were organized in a spreadsheet with columns including demographic features such as Age, Education Level, Occupation, Income Level, and Household Size, and waste features such as Fabric Waste (FW), Paper and Cardboard Waste (PCBW), Metal Waste (MW), Glass Waste (GW), Other Waste (OW), Plastic Waste (PW, sum of PETW, HDPEW, PVCW, LDPEW, PPW, PSW, and OPW), and Total Waste (TW, sum of FW, PCBW, MW, GW, OW, and PW). The analysis used Python libraries and packages, including NumPy, matplotlib, seaborn, sklearn, and pandas, (Python Software Foundation, Wilmington, DE, USA).

A feature matrix was created to combine demographics and waste for data preparation. The data were standardized using StandardScaler from the sklearn library to ensure a mean of 0 and a standard deviation of 1. This step is crucial as it prevents features with larger magnitudes from disproportionately influencing the clustering results. Then, Principal Component Analysis (PCA) was applied to the standardized features to identify the directions of maximum variance in each feature. This technique reduces the dimensionality of the dataset while preserving most of the variance. Top features were selected for further analysis based on their contributions to the principal components. The data preparation also included UMAP (Uniform Manifold Approximation and Projection), which was applied to reduce the dimensionality of the data while preserving its structure. This technique helps to create a low-dimensional representation of the data that preserves the local structure, making it easier to understand the underlying patterns. The above steps are critical to cluster the samples by applying the machine learning technique.

K-means clustering was used to segment the data into clusters. The number of clusters varied from 3 to 7 to determine the optimal number of clusters. Then, the silhouette score was calculated for each clustering solution to evaluate the quality of the clusters. The silhouette score measures how similar an object is to its cluster compared to others, with higher scores indicating better-defined clusters. Then, the number of clusters with the highest silhouette score was selected as the optimal clustering solution. Finally, ANOVA analysis was performed on the TW variable to assess the statistical significance of differences between clusters.

3. Results

The results section follows the structure outlined in the methodology. First, it presents a detailed description of the case study (Section 3.1). This is followed by the outcomes of the comparative LCA for the different recycling rate scenarios (Section 3.2). Next, the sensitivity analysis is addressed using the waste recovery indicator (Section 3.3) and, finally, the section concludes with a statistical analysis based on the survey conducted in the study area (Section 3.4).

3.1. Case Study

For the case study, the model developed for recycling different types of domestic recyclable waste is tested with actual data predicted in previous work [23]. Table 6 shows the total predicted quantities of the five groups of recyclable waste (plastic, glass, paper and cardboard, metal, and textiles). For each fraction, different sub-fractions have been identified following the information in Section 2.2. The area of Grand Guayaquil generates approximately 1740 tons of valuable MSW weekly. Plastic waste and paper and cardboard are the fractions with the most significant generation, approximately 74% (Table 6).

Table 6. Domestic recyclable waste generation and composition for the Grand Guayaquil Area.

Waste Fractions	Quantity *	Percentages **	EaseTech Waste	EaseTech Percentage **
Plastic	939.95	54.07		
PETW	144.29	21.14	Plastic bottles	23.10
PPW	367.48	8.30	Hard plastic	14.40
HDPEW	122.45	7.04		
LDPEW	122.33	7.04	Soft plastic	17.00
PSW	102.08	5.87	Non-recyclable plastics	1.00
OPW	75.51	4.34		
PVCW	5.82	0.33		
Paper and Cardboard	344.26	19.80		
Magazines and Advertising	68.75	3.96	Newsprint	3.10
Newsprint	55.39	3.19	Magazines	2.50
Office/Administrative Paper	34.32	1.97	Office paper	6.80
Books	2.38	0.14	Dirty cardboard	5.50
Cardboard and Paperboard	77.66	4.47	Paper and carton containers	3.00
Tissue Paper	51.54	2.96	Other clean cardboard	2.10
Other Paper	54.22	3.12		
Metal	185.60	10.68		
Tin-Plated Steel	100.22	5.77	Fe scrap	0.90
Stainless Steel	27.84	1.60	Food cans	0.30
Aluminum	42.69	2.46	Aluminum foil and containers	0.60
Other Metals	12.99	0.75	Copper	0.60
Non-Metals	1.86	0.11		
Glass	179.59	10.33		
Packaging Container	153.93	8.86	Clear glass	13.40
Table and Kitchenware	17.10	0.98		
Other/Special	8.55	0.49		
Textile	88.84	5.11		
Clothing	42.64	2.45	Textiles	5.60
Household Textiles	19.55	1.12		
Other Textiles	26.65	1.53		
Total	1738.25	100.00		100.00

* Quantities in tons/week. ** Percentages are in terms of mass.

To simulate the landfill domestic solid waste inflow from Guayaquil, the waste categories are grouped with similar waste types found within the EaseTech® database. The last two columns of Table 6 present the fractions of different categories in Grand Guayaquil’s MSW and the corresponding waste types used for the simulation.

3.2. Life Cycle Comparison

The baseline scenario (Scenario A) exhibits significant environmental impacts, primarily due to greenhouse gas emissions from landfill operations (Figure 4), particularly from the decomposition of biodegradable materials such as paper, cardboard, and textiles. These materials are prone to anaerobic decomposition within the landfill, releasing substantial amounts of greenhouse gases. For instance, the degradation of organic matter within the landfill can lead to an estimated emission of 1117 kg CO₂ eq ton of confined waste, underscoring the considerable environmental burden associated with the landfill. The sensitivity analysis shows that increasing the recycling rate significantly reduces these environmental impacts by diverting biodegradable materials away from landfills. Higher recycling rates also result in increased environmental credits by substituting virgin materials.

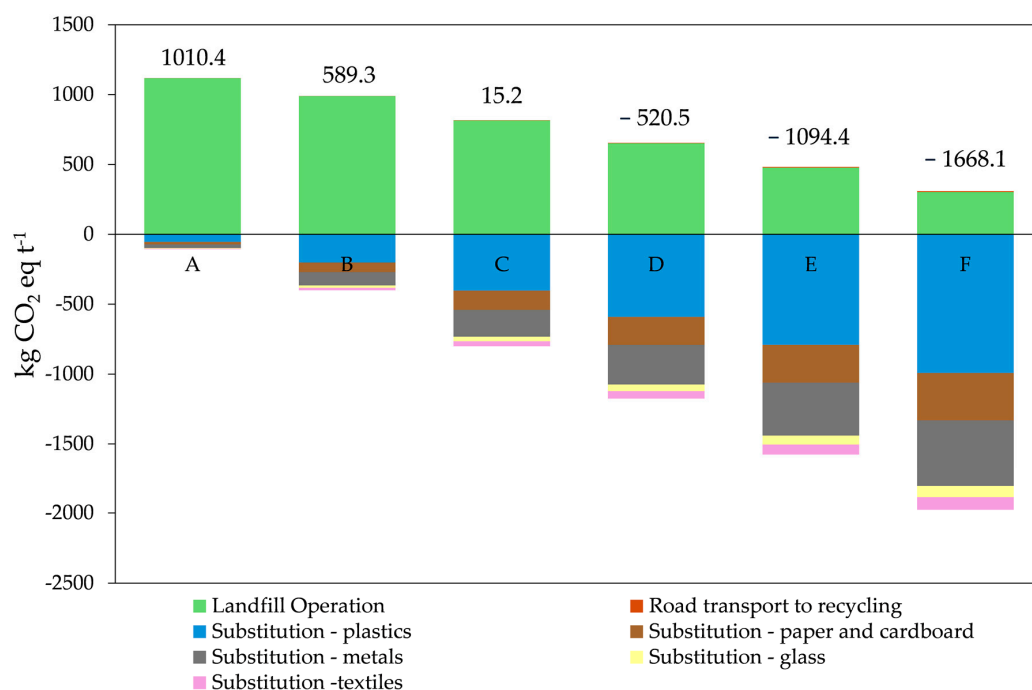


Figure 4. Global warming indicator results for the internal recycling scenario. A: base scenario; B: recycling rate of 20% scenario; C: recycling rate of 40% scenario; D: recycling rate of 60% scenario; E: recycling rate of 80% scenario; F: recycling rate of 100% scenario.

For example, in Scenario F, avoiding virgin material use, particularly in producing plastics, metals, and paper, can provide environmental benefits up to −1806 kg CO₂ eq ton of confined waste. These facts illustrate the critical role of recycling in mitigating the global warming potential of MSW management systems.

The fossil resource scarcity indicator (Figure 5) reveals that even a modest recycling rate of 6% is sufficient to offset the environmental impacts of landfill operations; this is primarily because the recycling process helps conserve fossil resources by reducing the demand for virgin materials, which are typically derived from fossil fuels. However, it is crucial to note that the boundaries of this study do not account for the emissions associated with waste transportation to the disposal site. These emissions could potentially alter the overall impact of the landfill operations. Nonetheless, similar to the global warming indicator, the sensitivity analysis shows that, as recycling rates increase, the environmental credits from substituting virgin materials—especially for producing plastics, metals, and paper—rise significantly. This trend makes the environmental impacts of the landfill process almost negligible.

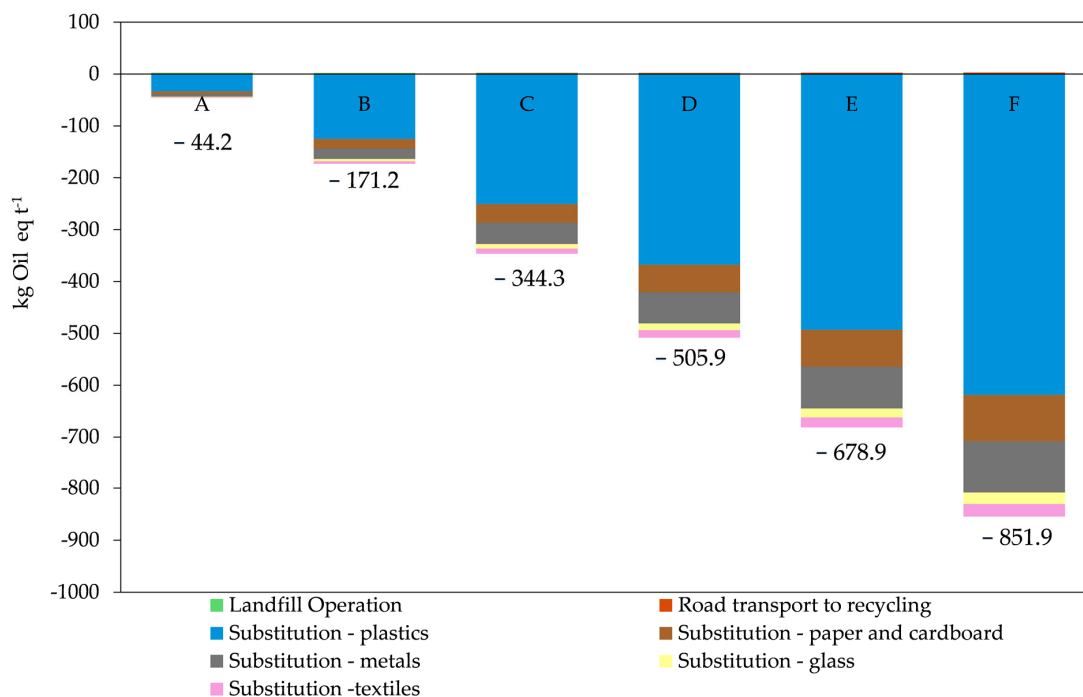


Figure 5. Fossil resource scarcity indicator results for the internal recycling scenario. A: base scenario; B: recycling rate of 20% scenario; C: recycling rate of 40% scenario; D: recycling rate of 60% scenario; E: recycling rate of 80% scenario; F: recycling rate of 100% scenario.

The terrestrial ecotoxicity indicator (Figure 6) follows a trend nearly identical to the fossil resource scarcity indicator. As recycling rates increase, reducing the need for virgin material production leads to a substantial decrease in the environmental toxicity burden on terrestrial ecosystems, further emphasizing the importance of recycling in minimizing the ecological footprint of waste management practices.

Figures 7–9 show the results for the global warming, fossil resource scarcity, and terrestrial ecotoxicity indicators of the foreign recycling scenario. Analyzing domestic and foreign recycling scenarios reveals that the global warming indicator (Figure 7) and fossil resource scarcity indicator (Figure 8) show similar trends. In both scenarios, the environmental benefits derived from substituting virgin materials in producing metals, plastics, and paper far outweigh the environmental impacts associated with landfill operations and the transportation of recyclable materials. Specifically, the reduction in greenhouse gas emissions and fossil resource consumption achieved through the recycling of these materials is substantial, regardless of whether the recycling occurs locally or in foreign facilities. This consistency across scenarios highlights the robustness of recycling as a strategy for mitigating climate change and conserving finite resources, underscoring its critical role in advancing sustainable waste management practices in Latin America.

A divergence appears when analyzing the terrestrial ecotoxicity indicator (Figure 9). In the external recycling scenario, where recyclable materials are transported to other countries for valorization, the terrestrial ecotoxicity impacts increase notably with higher recycling rates. This situation is primarily due to the contributions from both terrestrial and maritime transportation. As the recycling rate increases, so does the volume of materials that must be transported, leading to higher emissions of pollutants and other harmful substances during transit. These transportation-related impacts contribute significantly to the overall ecotoxicity burden, potentially compromising the recycling process’s environmental profile. Despite the observed increase in ecotoxicity impacts, it is essential to note that these impacts remain lower than the environmental credits gained from substituting virgin materials, suggesting that, while external recycling is environmentally viable, careful consideration must be given to the transportation impacts, as they can represent a critical environmental

hotspot. The results indicate that the benefits of material recovery and recycling still outweigh the negative impacts, but optimizing the transportation logistics could further enhance the environmental performance of the external recycling scenario.

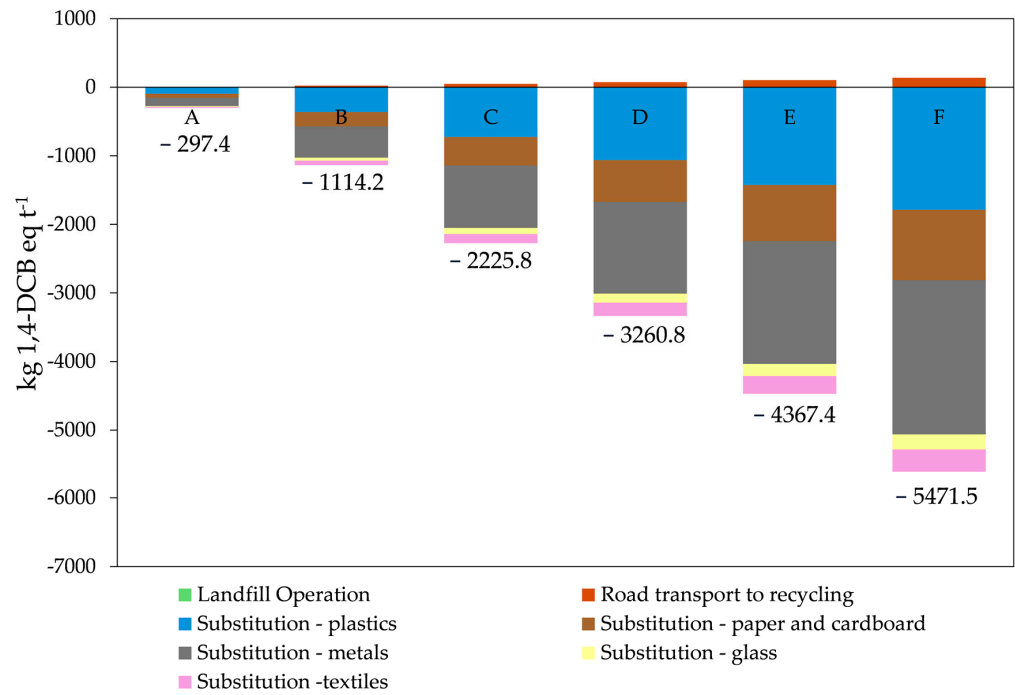


Figure 6. Terrestrial ecotoxicity indicator results for the internal recycling scenario. A: base scenario; B: recycling rate of 20% scenario; C: recycling rate of 40% scenario; D: recycling rate of 60% scenario; E: recycling rate of 80% scenario; F: recycling rate of 100% scenario.

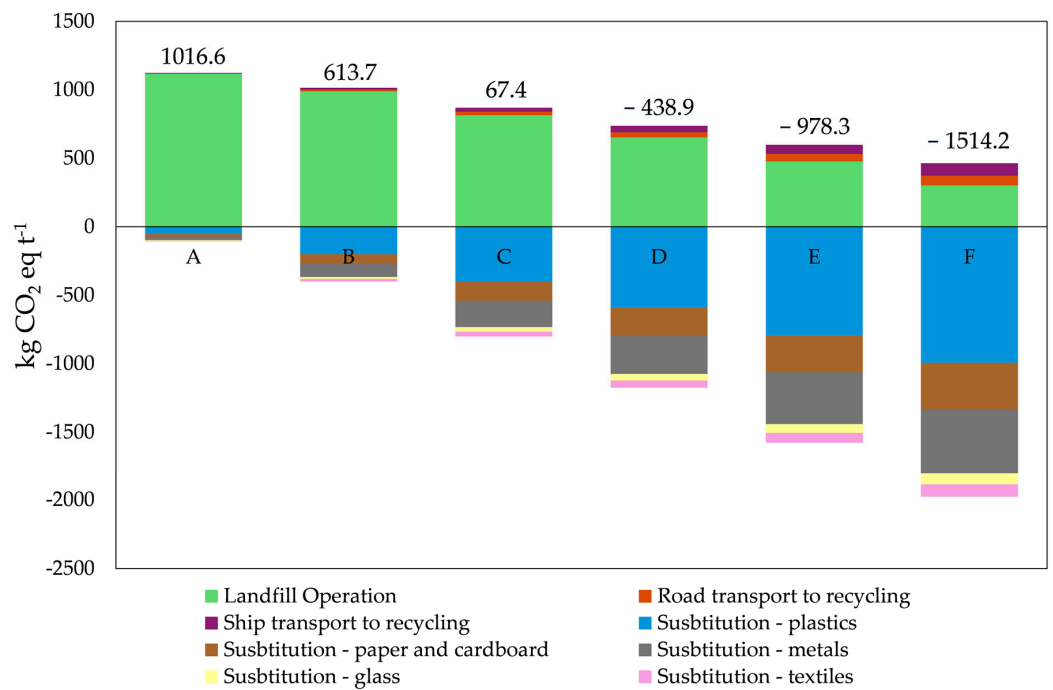


Figure 7. Global warming indicator results for the external recycling scenario. A: base scenario; B: recycling rate of 20% scenario; C: recycling rate of 40% scenario; D: recycling rate of 60% scenario; E: recycling rate of 80% scenario; F: recycling rate of 100% scenario.

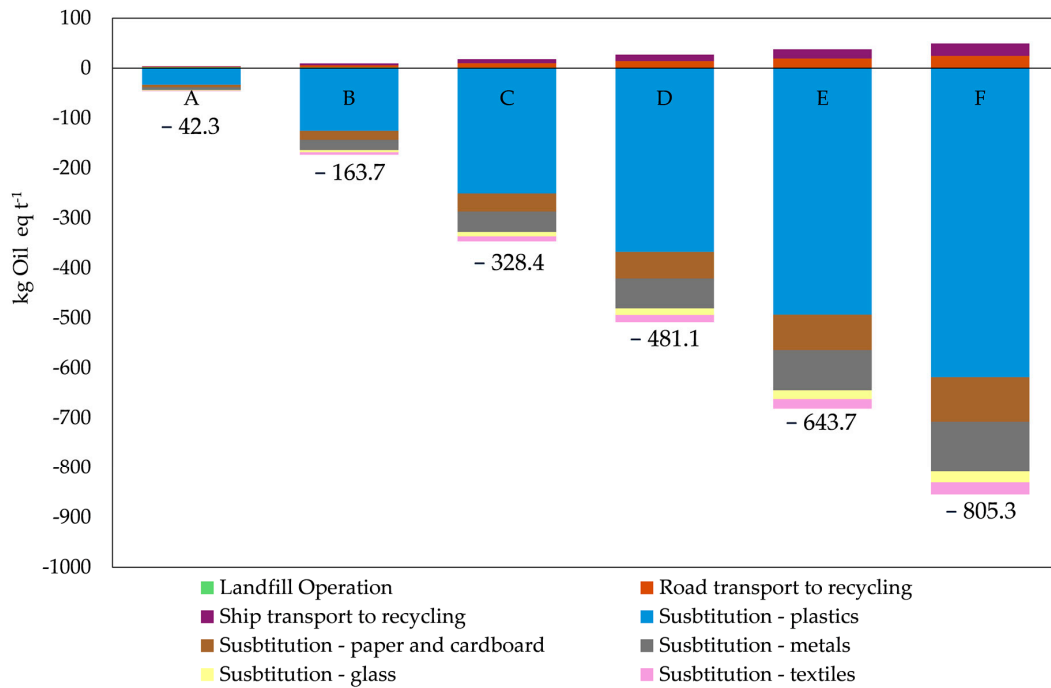


Figure 8. Fossil resource scarcity indicator results for the external recycling scenario. A: base scenario; B: recycling rate of 20% scenario; C: recycling rate of 40% scenario; D: recycling rate of 60% scenario; E: recycling rate of 80% scenario; F: recycling rate of 100% scenario.

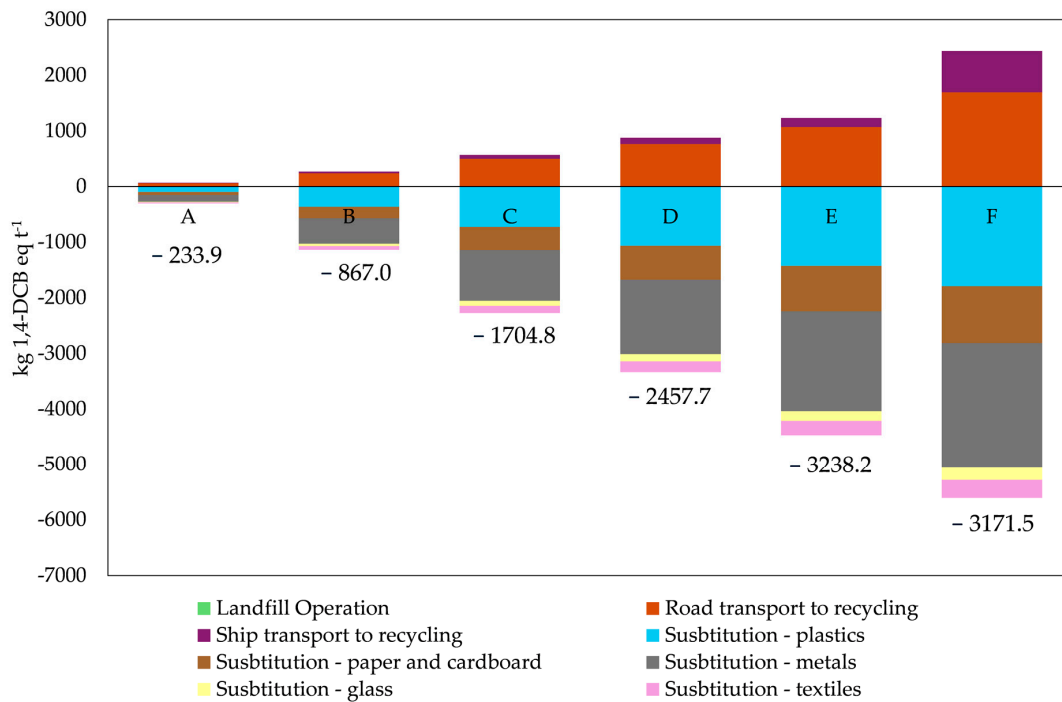


Figure 9. Terrestrial ecotoxicity indicator results for the external recycling scenario. A: base scenario; B: recycling rate of 20% scenario; C: recycling rate of 40% scenario; D: recycling rate of 60% scenario; E: recycling rate of 80% scenario; F: recycling rate of 100% scenario.

3.3. Recyclability Rate

The waste recovery indicator (WRI) was calculated to measure the circularity of waste generated in the Grand Guayaquil Metropolitan Area, relative to its generation. The WRI was determined for all waste categories, taking into account their potential for closed-loop

recycling (Table 1). The overall WRI for waste generated in Greater Guayaquil is 0.044, indicating that 4.4% of the total waste mass is recovered and diverted from landfills towards recycling and reuse processes. This global WRI reflects the potential efficiency of the waste management system and highlights the areas for improvement [57].

The baseline WRI values for plastics (Figure 10) such as PETW, PPW, HDPEW, and LDPEW are relatively low, reflecting the limited recovery and recycling efforts in the current scenario of Grand Guayaquil, where only 6% of waste is recycled. For instance, the WRI for PET starts at 0.011, which increases to 0.190 when the recycling rate reaches 100%. This substantial increase highlights the potential for significant improvements in material recovery and reduction in environmental impact with higher recycling rates [58]. Similar trends are observed in the category of paper and cardboard.

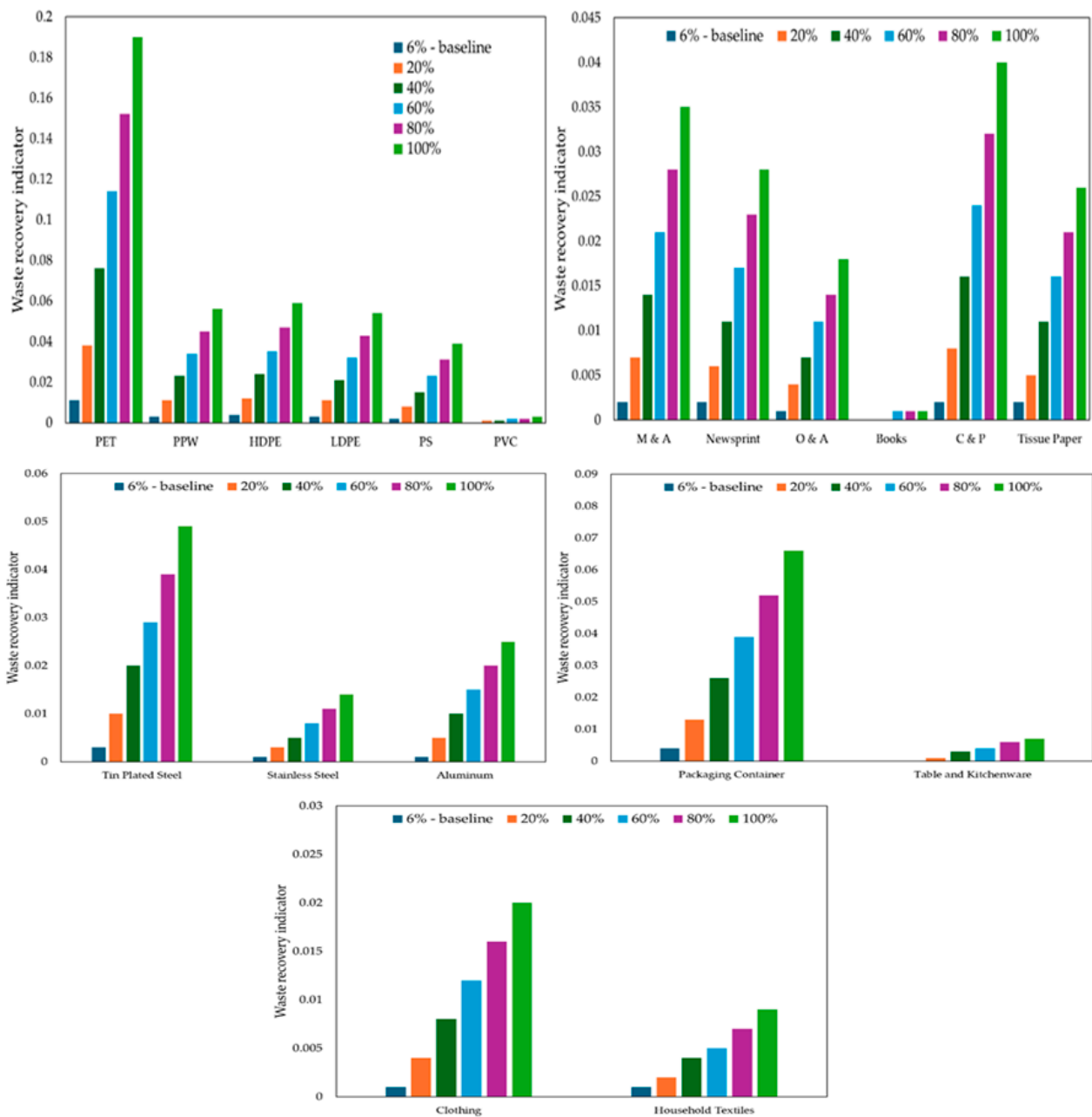


Figure 10. Waste recovery indicator for plastics, paper and cardboard, metals, glass, and textiles. PET: polyethylene terephthalate; PPW: polypropylene waste, HDPE: high density polyethylene; LDPE: low density polyethylene; PS: polystyrene; PVC: polyvinyl chloride; M&A: magazines and advertising; O&A: office and administrative paper; C&P: cardboard and paper.

For materials like magazines and advertising papers, the WRI starts at 0.002 under the current recycling rate and increases to 0.035 at a 100% recycling rate. This trend underscores the importance of enhancing recycling efforts for paper products, which not only contribute to waste reduction but also to the conservation of resources and reduction in greenhouse gas emissions. The WRI for metals and glass also demonstrates significant improvements with increasing recycling rates. These materials are highly recyclable, and their recovery can lead to substantial environmental benefits, including the reduction of energy consumption in the production of virgin materials and the minimization of waste sent to landfills. Textiles, although typically more challenging to recycle due to mixed material composition, show a similar positive trend in WRI with increased recycling efforts.

As the recycling rate increases, the recovery of textile materials becomes more efficient, reflecting the potential for innovation and improvement in textile recycling technologies. These results provide a promising outlook for the transition towards a circular economy in Latin America. By increasing the recycling rates, cities like Guayaquil can significantly enhance the recovery of valuable materials, thereby reducing the environmental footprint of waste management systems. This transition is particularly critical in Latin American contexts where the waste management infrastructure is often underdeveloped, and landfilling remains the predominant method of waste disposal.

Moreover, the positive trends in WRI with increased recycling rates demonstrate that substantial environmental and economic benefits can be realized by adopting more aggressive recycling strategies. This includes not only the direct recovery of materials but also the associated reductions in greenhouse gas emissions, energy consumption, and the conservation of natural resources. The sensitivity analysis of WRI across different recycling scenarios underscores the critical role of recycling in achieving a circular economy. By prioritizing and expanding recycling efforts, cities in Latin America can move towards more sustainable and resilient waste management systems, ultimately contributing to global sustainability goals.

3.4. Correlation Analysis

During the data acquisition for the study area of Grand Guayaquil, a survey was conducted on 797 families [23]. After data preparation, 793 samples were considered for the analyses presented below. Figure 11 presents the PCA loadings heatmap, which shows the contribution of each feature to the principal components to reduce dimensionality while retaining as much variance as possible. For example, TW, PW, and PCBW capture the maximum variance in the data for PC1. This step is crucial to preserving most of the information while reducing complexity. When each feature is ranked by its overall importance in the dataset, the most important features are Household Size, OW, and PCBW. TW has the lowest importance based on the PCA loadings, indicating it contributes the least to the variance captured by the PC. This suggests that TW likely dampens variances by aggregating the contributions of the other waste types into a single feature.

The K-means clustering separates the 793 samples based on the similarity (or distance) between data points in the feature space. The silhouette score was used to measure this similarity; the higher the score, the better the differentiation of the clusters. Figure 12 presents the results of the silhouette score and based on these results four clusters were created. Specifically, K-means uses the Euclidean distance to measure how close each data point is to the cluster centroids, ensuring the four clusters are distinct from each other.

Another way to test the differentiation of each cluster was through ANOVA, performed for each of the waste features. The results of the ANOVA show a p-value of less than 0.05 and a high F-statistic, indicating substantial differences in each waste feature between clusters.

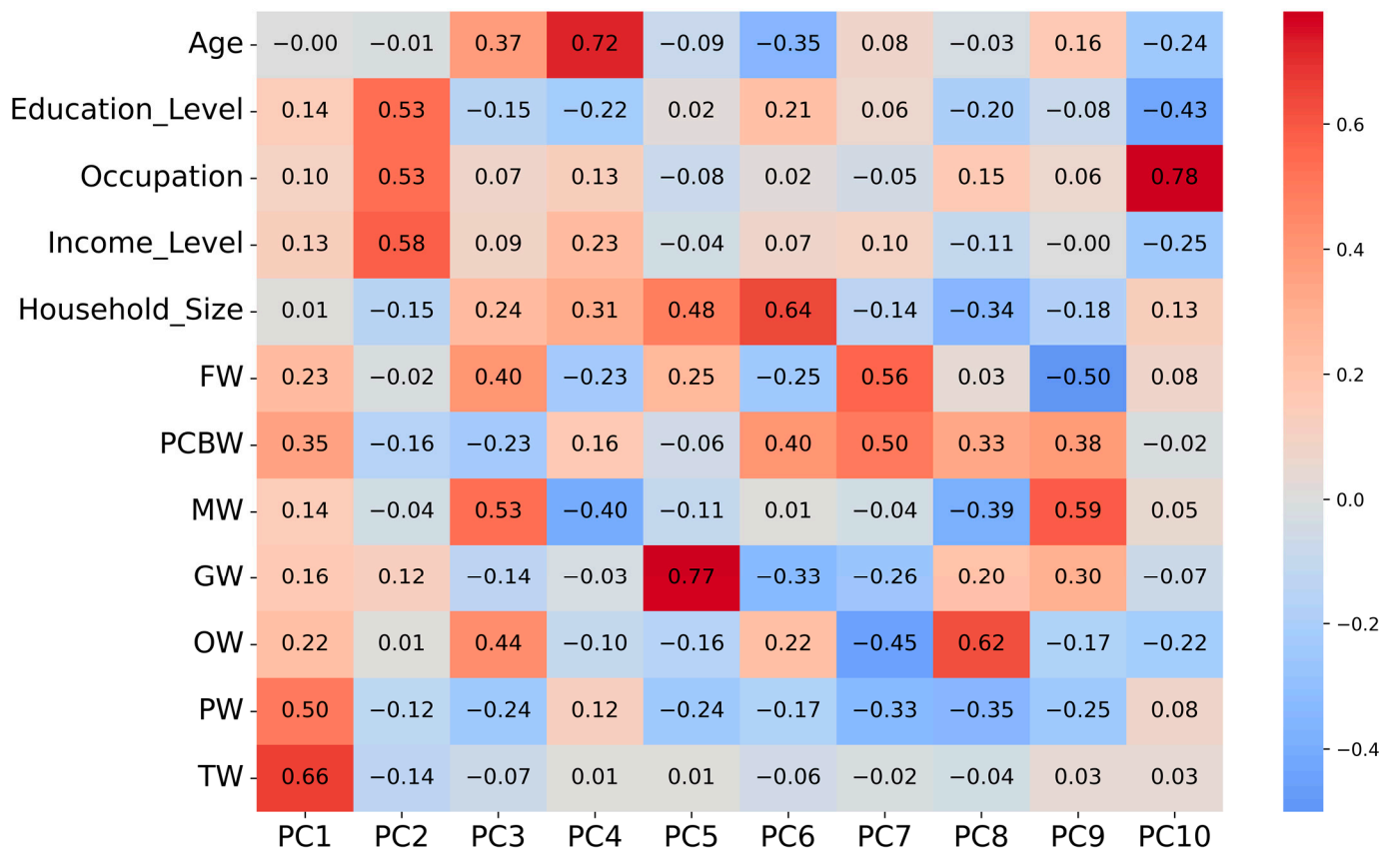


Figure 11. PCA loading heatmaps between the principal components and the features.

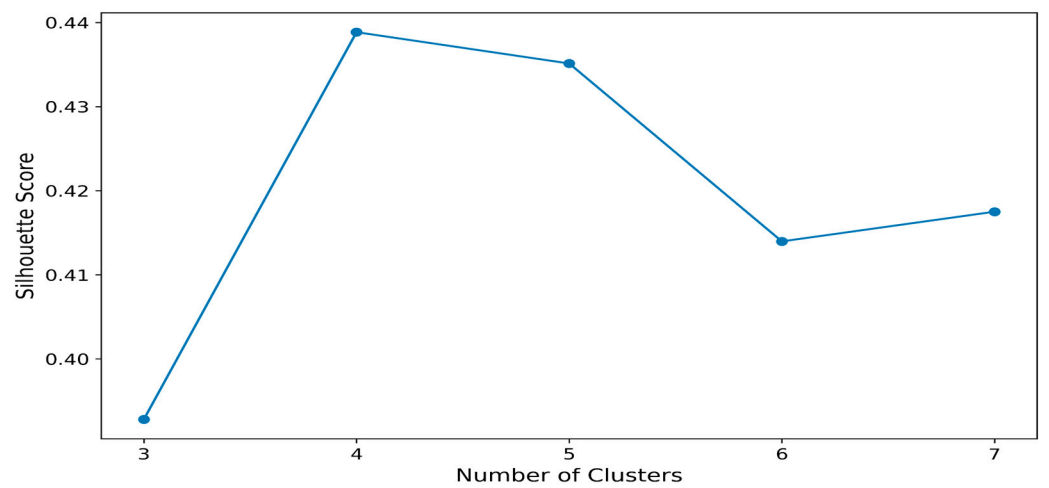


Figure 12. Optimal number of clusters based on the silhouette score.

Figure 13 shows the distribution of the demographic features between the clusters. Demographic information allows for classifying each group and characterizing the population, finding correlations between demographic features and waste production.

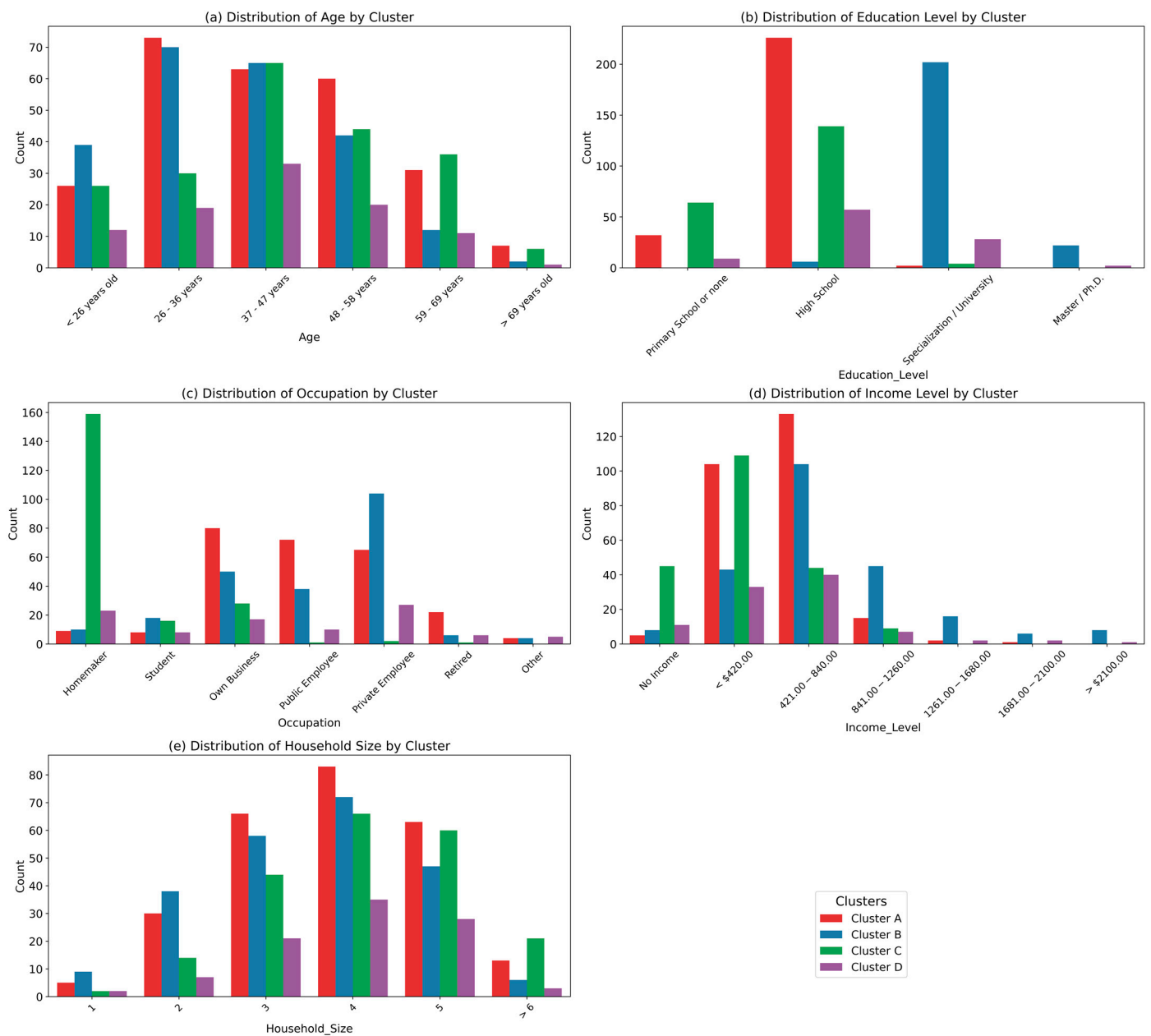


Figure 13. Distribution of the demographic characteristics for each cluster.

Cluster A includes 260 samples, predominantly younger adults (26–47 years) with high school education, primarily employees and business owners, with incomes below USD 840 and average household sizes. This cluster represents the entrepreneurial middle class of the Grand Guayaquil Metropolis without access to higher education but with their businesses, allowing them to earn average incomes of twice the minimum wage in Ecuador (USD 460 in 2024, according to the Ministry of Labor of Ecuador [59]).

Cluster B includes 230 samples of slightly younger adults with higher education levels, mostly private employees, with higher incomes. This cluster represents the educated young population of the Grand Guayaquil Metropolis working in the private sector with the highest incomes.

Cluster C includes 207 samples with a broad age range, significantly represented by those aged 59–69 years, with lower education levels (high school and primary school), mostly homemakers, lower-income levels, and larger household sizes. This cluster includes

the elderly population of the Grand Guayaquil Metropolis, typically out of the labor market (homemakers), without income but living in large houses with more than six rooms.

Cluster D includes 96 samples with average levels across all categories, showing no particular demographic characteristics. The machine learning model separated this group as a particular case with average features whose waste characteristics differ from the other clusters.

Figure 14 presents the heatmap for the clusters created from the K-means clustering algorithm, relating the waste features (x-axis) and the demographic features (y-axis). The colors represent the Pearson coefficient, where higher values imply a positive correlation. If the correlation coefficient is close to 0, it indicates no correlation, meaning no linear relationship between the features. Although each cluster has particular minimum and maximum values, the correlation range was homogenized from -0.23 to 0.31 .

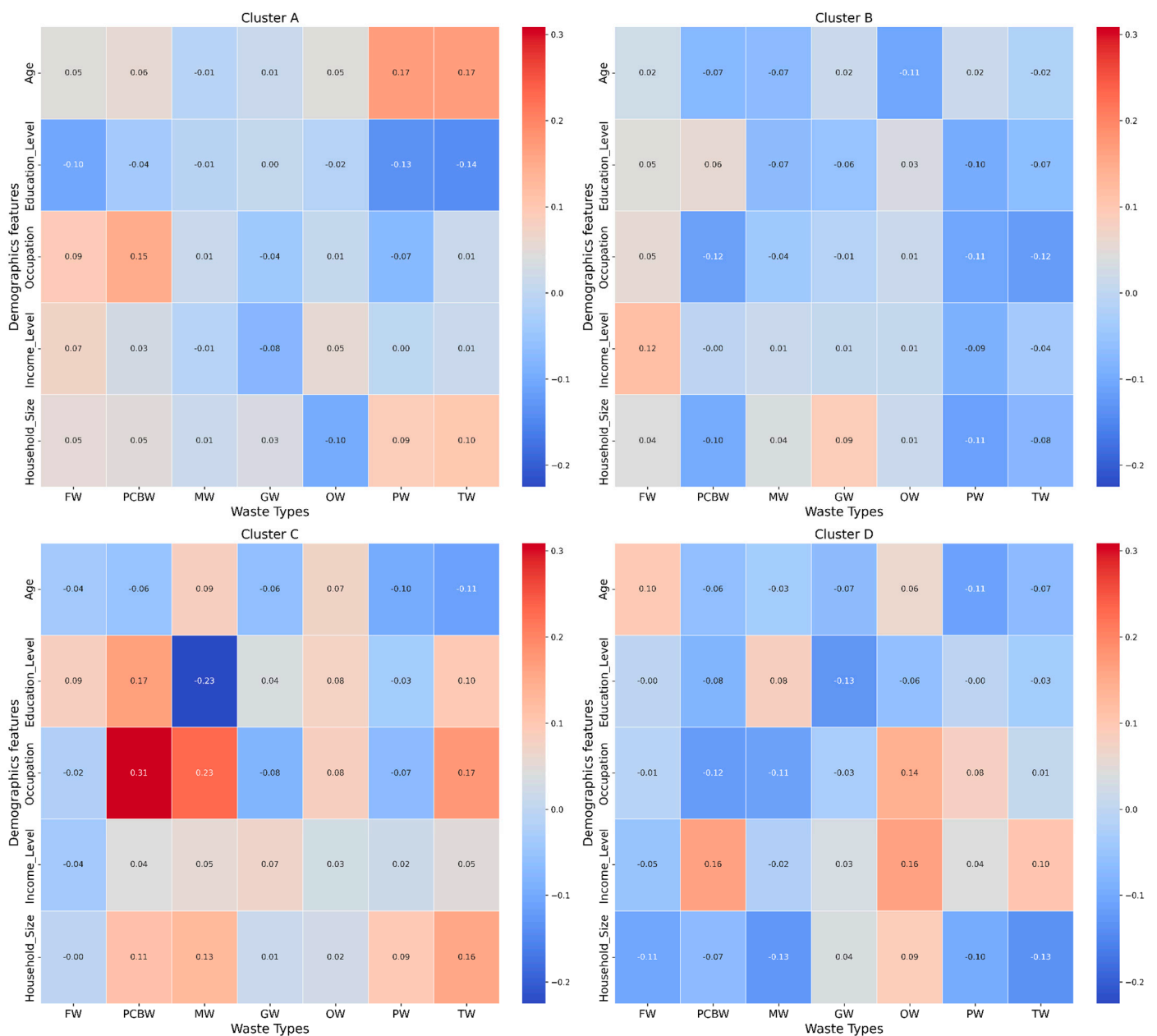


Figure 14. Heatmaps between demographics features and waste features. FW: fabric waste, PCBW: paper and cardboard waste, MW: metal waste, GW: glass waste, OW: other waste, PW: plastic waste, and TW: total waste.

Figure 15 presents the distribution of waste features by cluster. These results can be interpreted alongside Figure 13, as the differences and similarities in waste features are associated with the demographic ones. Cluster D shows a higher interquartile range (IQR) in some types of waste, indicating that it contains the 96 samples that do not fit into the other clusters. TW exhibits moderate variation, which aligns with the PCA loadings heatmap interpretation (Figure 11). This suggests that, although each cluster is different, the quantities of waste are not as critical for differentiating the clusters as the demographic features are.

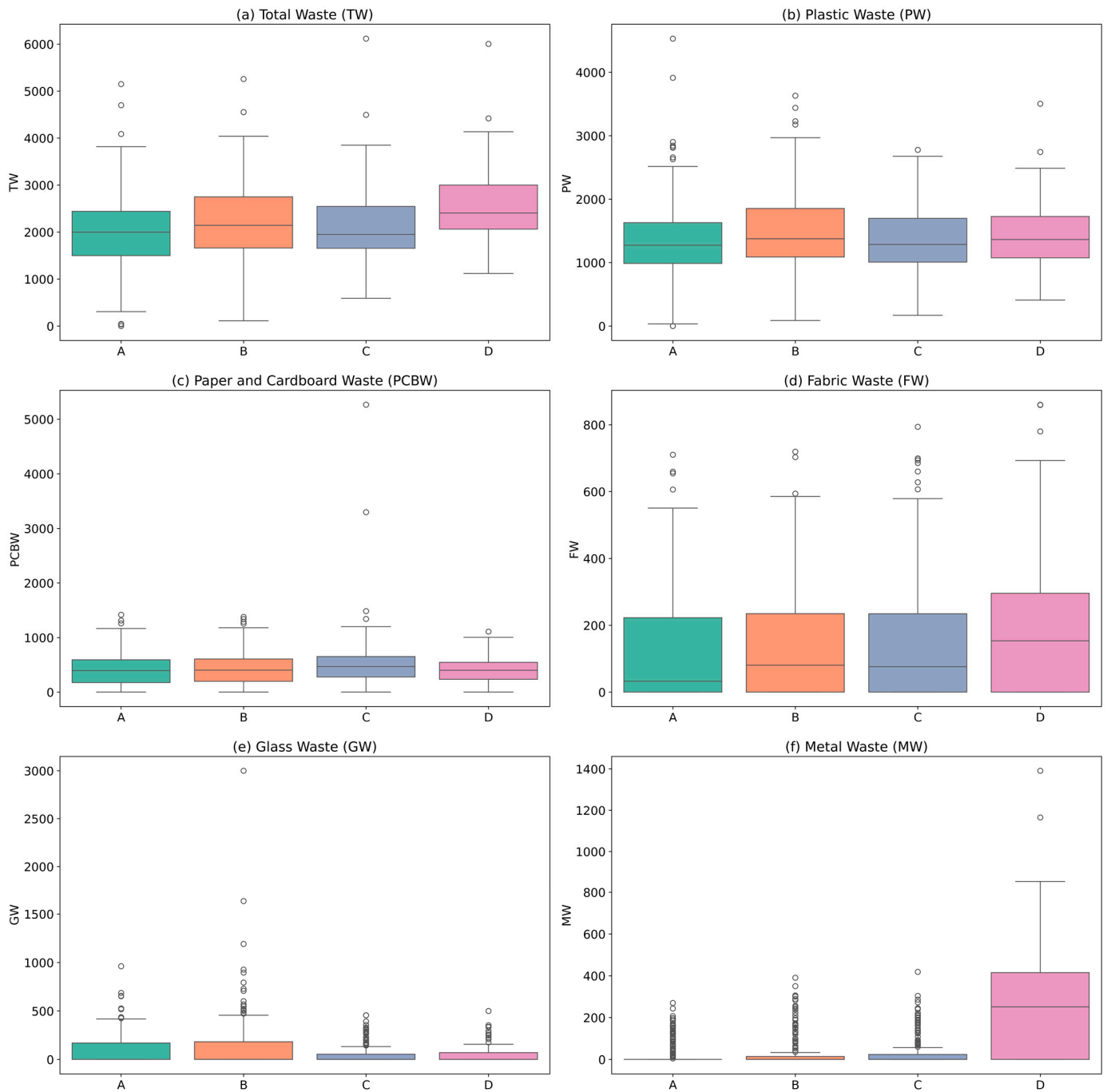


Figure 15. Distribution of waste features by cluster in order (A to D) from left to right (a) Total waste, (b) plastic waste, (c) paper and cardboard waste, (d) fabric waste, (e) glass waste, and (f) metal waste.

Although Figures 13 and 14 may give an idea of the relationship between demographic features and waste features, in order to analyze these results, it must be emphasized that demographic aspects are categorical variables and that a correlation does not imply causation or interaction.

Although Figures 14 and 15 may give an idea of the relationship between demographic features and waste features, in order to analyze these results, it must be emphasized that demographic aspects are categorical variables and that a correlation does not imply causation or interaction. For Cluster A, represented by the middle class, there is a positive correlation between age and waste generation, which could indicate that older individuals tend to generate more waste. For Cluster B, represented by the young and educated population, there is evidence that higher income levels tend to generate more PW. For Cluster C, characterized by the elderly low-income population, there is an association between homemakers and lower TW. For Cluster D, average demographic characteristics are moderately associated with higher waste generation.

4. Discussion

The comparison between domestic and foreign recycling scenarios in Guayaquil demonstrates that both approaches effectively reduce the environmental impacts associated with waste management. The consistency of the global warming and fossil resource scarcity indicators across both scenarios emphasizes the overall benefits of recycling. However, the increased terrestrial ecotoxicity in the external scenario highlights the need for strategic interventions to minimize transportation impacts, ensuring that recycling efforts contribute positively to the broader goals of sustainability and circular economy transitions in Latin America. The findings underscore that, while external recycling is a viable option, especially in regions with limited local recycling infrastructure, attention must be paid to the environmental costs associated with transporting materials. This finding aligns with previous studies, which showed similar benefits in developing regions with a limited recycling infrastructure. However, in the external scenario, the increase in terrestrial ecotoxicity due to transportation impacts suggests that strategic interventions are necessary to mitigate these effects, ensuring that recycling efforts positively contribute to sustainability goals [60].

The results from Section 3.4 reveal distinct differences in waste generation patterns across various demographic clusters, influenced by factors like age, income, and household size. Higher income levels generally correlate with increased waste generation, though this varies by cluster. This result aligns with the findings of previous studies that also identify significant variations in waste generation according to socioeconomic class in Latin American cities [61]. These findings emphasize the importance of tailoring waste management policies to the specific characteristics of each demographic group, particularly within a circular economy framework.

The LCA results suggest that increasing recycling rates universally reduces environmental impacts. This result is in line with that of a previous study which validated that an increased plastic recycling fraction could decrease the environmental impacts of global warming by a margin of 20–45% and fossil resource scarcity by a margin of 20–52% [62]. However, the demographic analysis indicates that different populations contribute to and are affected by waste management efforts in different ways. For instance, older, lower-income populations (Cluster C) might generate less waste but also have less capacity to engage in recycling programs. This introduces challenges that need to be addressed by integrating economic, logistical, geographic, and environmental aspects between the stages of product use and final disposal.

With diminishing space for landfills and the rising costs of solid waste management, the need for urban solid waste recycling has become increasingly important. Establishing a commercial infrastructure to support recycling is essential for reducing the amount of waste sent to landfills. Waste transfer stations, effective in other large cities in the LATAM region, can play a critical role by encouraging recycling, minimizing illegal dumping, and offering a convenient, cost-effective location for waste drop-off. However, identifying optimal

locations for waste management facilities is a complex process that requires considering factors like population density, road networks, and administrative policies.

The domestic recycling scenario in the LCA study shows 154 kg CO₂ of environmental credits more than the foreign scenario for recycling rate of 100%, suggesting that efforts to export waste may not favor the external scenario. However, these results need to be complemented with economic studies that emphasize the infrastructure needs and include specific eco-inventories for Ecuador's conditions. Another important factor to consider is the efficiency of recycled material production (Ri). In this study, the same factors were considered for both internal and external recycling scenarios, which may not be entirely accurate and could explain why environmental credits increase similarly in both scenarios as the recycling rate increases. Currently, there is no specific information in Ecuador that allows for adjusting the eco-inventories to the country's specific conditions. For this information to be useful in decision making, it is necessary to evaluate the factors provided in Table 1 within the context of Guayaquil. While scientific contributions from external articles are valuable as reference points, they are insufficient without specific data on local conditions.

In addition to the environmental credits observed, another crucial metric for assessing the sustainability of recycling systems is the waste recovery indicator (WRI). This indicator measures the efficiency of waste management systems in diverting municipal solid waste (MSW) from landfills by quantifying the proportion of waste recovered through recycling, composting, or other recovery processes relative to total MSW generated. In both the domestic and external recycling scenarios, the WRI could provide a valuable perspective on the effectiveness of waste recovery efforts, highlighting not only the environmental impacts but also the broader resource conservation benefits. A higher WRI indicates a more efficient system that aligns with circular economy goals, as it demonstrates the reintegration of waste materials into the production cycle and reduces the need for virgin materials. By incorporating the WRI into future assessments, policymakers and stakeholders could gain a clearer understanding of the extent to which recycling efforts contribute to both sustainability and circularity, complementing the existing environmental impact data from this study.

The results of this study have important policy implications for waste management system governance, particularly with regard to improving recycling activities. One potential area for improvement is the creation of more robust frameworks for managing both internal and external recycling systems [63]. The introduction of these frameworks could streamline decision making, improve the efficiency of recycling processes, and optimize the allocation of the resources needed for waste management. Such frameworks could play a key role in minimizing inefficiencies, such as the environmental costs of transport observed in external recycling scenarios, while ensuring that recycling initiatives are aligned with national and local sustainability goals [64]. Conversely, the adoption of policies that do not reflect market realities can undermine recycling efforts. For example, Ecuador presents the "Organic Law for the Rationalization, Reuse, and Reduction of Single-Use Plastics" which mandates that each PET bottle manufactured must contain at least 15% recycled material by 2022, with progressive increases each year [65]. However, this initiative has paradoxically led to increased plastic imports because it was not accompanied by incentives for recycling infrastructure and education [58].

One crucial factor in planning effective waste collection and treatment strategies is the geographic location of the samples [66]. For instance, targeting high-income areas like Cluster B, which generates more waste, could significantly enhance environmental outcomes. To achieve this, it is essential to identify areas within the city that align with these clusters, allowing for focused efforts on increasing recycling rates where they would have the greatest impact.

Some limitations of this study include the lack of information on the fraction of valuable solid waste separation, the efficiency of recycled material production, and the efficiency of virgin material substitution. Future efforts should focus on finding case studies

specific to Guayaquil to improve the precision of the proposed model. Additionally, an economic study that calculates waste treatment costs for both internal and external scenarios is recommended, as transportation, though relatively low in environmental impact, could be a key factor in economic terms. Finally, a statistical study on the composition of waste at collection centers geographically located in the city could be crucial for improving the accuracy of the created clusters and thereby better contributing to the segmentation of waste reduction strategies in communities.

5. Conclusions

This study provides a comprehensive analysis of domestic solid waste management in the Grand Guayaquil area, emphasizing the environmental and logistical implications of recycling. Through life cycle assessment (LCA), we compared the impacts of domestic and external recycling scenarios, highlighting the significant benefits of increased recycling rates across various environmental indicators, including global warming potential, fossil resource scarcity, and terrestrial ecotoxicity. The results indicate that, while both domestic and external recycling scenarios reduce environmental impacts, domestic recycling offers slightly higher environmental credits, particularly in terms of greenhouse gas emissions.

The demographic analysis revealed distinct patterns in waste generation and recycling potential across different population clusters. Higher-income and younger populations tend to generate more waste, underscoring the need for tailored waste management policies that address the specific characteristics of these groups. Furthermore, the sensitivity analysis demonstrated that increasing the recycling rate significantly enhances the waste recovery indicator (WRI), moving the region closer to a circular economy.

However, the study also identifies challenges, such as the need for improved infrastructure, more accurate local data, and better integration of recycling initiatives with market realities. For instance, policies like Ecuador's mandate for recycled content in PET bottles must be supported by an adequate recycling infrastructure to avoid unintended consequences, such as increased plastic imports.

A number of Sustainable Development Goals (SDGs) are touched upon in the examination of recycling scenarios in Guayaquil. Promoting urban solid waste recycling, cutting back on landfill usage, and improving waste management infrastructure are ways to achieve SDG 11 (Sustainable Cities and Communities). Increased recycling rates, waste reduction, and the implementation of circular economy principles that reintegrate materials into the production cycle are all initiatives that highlight SDG 12 (Responsible Consumption and Production). The research also discusses SDG 13 (Climate Action), since recycling initiatives try to lessen the effects of global warming by better managing plastic waste and lowering CO₂ emissions. Additionally, SDG 17 (Partnerships for the Goals), which emphasizes cooperation between stakeholders and policymakers to create efficient waste management frameworks that complement national sustainability goals, is highlighted by the emphasis on local and external recycling methods.

Future efforts should focus on refining the model with more specific local data, conducting economic analyses of waste treatment costs, and exploring the geographic distribution of waste generation to optimize collection and recycling strategies. Overall, this research underscores the importance of enhancing recycling practices in Latin America to mitigate environmental impacts and move towards sustainable waste management.

Author Contributions: Conceptualization, J.H.-C. and P.R.-G.; methodology, J.H.-C., P.R.-G., E.E.G.-B., A.A.-R., S.Q.-H., J.L.A.R. and A.V.-M.; software, P.R.-G., E.E.G.-B., A.A.-R., S.Q.-H. and A.V.-M.; validation, J.H.-C., P.R.-G. and M.S.; formal analysis, J.H.-C., P.R.-G., E.E.G.-B., A.A.-R., S.Q.-H., J.L.A.R., A.V.-M. and M.S.; resources, J.H.-C., P.R.-G., E.E.G.-B., A.A.-R., S.Q.-H. and A.V.-M.; data curation, J.H.-C. and S.Q.-H.; writing—original draft preparation, J.H.-C., E.E.G.-B., A.A.-R. and S.Q.-H.; writing—review and editing, P.R.-G., A.V.-M., J.L.A.R. and M.S.; visualization, P.R.-G., A.V.-M., J.L.A.R. and M.S.; supervision, J.H.-C., P.R.-G. and M.S.; project administration, J.H.-C. and P.R.-G.; funding acquisition, J.H.-C., A.V.-M. and M.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data will be made available on request.

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

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