ORIGINAL ARTICLE

Ecological footprint of recyclable municipal solid waste in Tacna (Peru)

Huella ecológica de residuos sólidos municipales reciclables en Tacna (Perú)

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ABSTRACT

Municipal solid waste management constitutes a critical challenge for the sustainability of intermediate cities in Latin America. In this study, we evaluated the ecological footprint (EF) associated with recyclable municipal solid waste in the Tacna district of southern Peru, from 2020 to 2024. Using data from the Solid Waste Management Information System (SIGERSOL), a quantitative and longitudinal approach was applied based on the ecological footprint model proposed by Wackernagel and Rees (1998) and adapted by Doménech (2010), in order to estimate the environmental pressure derived from the fossil energy embodied in municipal solid waste. The results revealed a marked heterogeneity in the ecological contribution of the different waste fractions. Fine paper recorded the highest average EF, followed by cardboard and high-density polyethylene (HDPE), whereas metals such as steel and iron exhibited the lowest relative contributions. Temporal analysis indicated an increasing trend in the pressure exerted by cardboard and HDPE in 2024. Principal component analysis (PCA) explained 96.1% of the total variability, with cellulosic and plastic materials identified as the main determinants of the environmental burden of the municipal system. Hierarchical clustering analysis confirmed the structural segregation between waste types with high and low ecological intensity. The conclusion of our study was that EF constitutes an effective diagnostic tool for urban planning, suggesting that public policies should prioritize the traceability and valorization of paper and plastic waste, in order to mitigate the pressure on local ecosystems.

Keywords: *ecological footprint, municipal solid waste, SIGERSOL, recycling, environmental management, Tacna*

RESUMEN

La gestión de residuos sólidos municipales representa un desafío crítico para la sostenibilidad de las ciudades intermedias en América Latina. Este estudio evaluó la huella ecológica (HE) asociada a los residuos sólidos municipales reciclables en la provincia de Tacna, distrito de Tacna, Perú, durante el periodo 2020-2024. Utilizando datos del Sistema de Información para la Gestión de Residuos Sólidos (SIGERSOL), se aplicó un enfoque cuantitativo y longitudinal basado en el modelo de huella ecológica propuesto por Wackernagel y Rees (1998) y adaptado por Doménech (2010), con el fin de estimar la presión ambiental derivada de la energía fósil incorporada en los residuos sólidos municipales. Los resultados revelaron una marcada heterogeneidad en la contribución ecológica de las diferentes fracciones de residuos. El papel fino registró la mayor HE promedio, seguido por el cartón y el polietileno de alta densidad (HDPE), mientras que metales como el acero y el fierro exhibieron las menores contribuciones relativas. El análisis temporal indicó una tendencia creciente en la presión ejercida por el cartón y el HDPE hacia 2024. El análisis de componentes principales (ACP) explicó el 96,1 % de la variabilidad total, al identificar a los materiales celulósicos y plásticos como los principales determinantes de la carga ambiental del sistema municipal. El análisis de agrupamiento jerárquico confirmó la segregación estructural entre tipos de residuos con alta y baja intensidad ecológica. Se concluye que la HE constituye una herramienta diagnóstica eficaz para la planificación urbana, sugiriendo que las políticas públicas deben priorizar la trazabilidad y valorización de residuos de papel y plástico con el fin de mitigar la presión sobre los ecosistemas locales.

Palabras clave: *huella ecológica, residuos sólidos municipales, SIGERSOL, reciclaje, gestión ambiental, Tacna*

1. Introduction

Ecological footprint (EF) is a physical indicator that enables the quantification of the impact of human activities on the environment. It represents the balance between resource consumption and availability, is measured in global hectares (GHA), and is useful for estimating pollution levels at both individual and population scales (Huamaní Peralta and Quispe Mamani, 2024). The measurement of ecological footprint estimates the biologically productive area required to satisfy human demands and assimilate generated waste, thereby providing a measure of the balance between anthropogenic pressure and the regenerative capacity of ecosystems (Chen and Pao, 2024; Ferrante *et al*., 2025). In this context, strategies such as recycling, waste management optimization and the implementation of circular economy models have been developed as effective mechanisms for reducing ecological footprint (Chen and Pao, 2024; Oo *et al*., 2024). Furthermore, this indicator can be divided into different components, including carbon, water, land and material footprints, each aimed at measuring a specific dimension of environmental impact and influenced by structural processes such as population growth and industrial intensification (Doménech, 2010). The mitigation of these impacts requires the adoption of comprehensive measures involving energy efficiency, sustainable mobility and strengthened environmental education (Chen and Pao, 2024; Ferrante *et al*., 2025).

In Peru, per capita ecological footprint has been estimated at 1.46 GHA/person, exceeding biocapacity limits (Huamaní Peralta and Quispe Mamani, 2024), while the significant differences identified between urban and rural contexts have been attributed to differentiated consumption patterns (Carpio, 2020). However, higher values, reaching 4.93 GHA/inhabitant/year, have also been reported, reflecting scenarios of ecological overshoot (Primo Ordoñez, 2022). In the construction sector, values of up to 3655.10 GHA and 2626.22 GHA have been identified in educational institutions, reflecting the influence of the levels of waste generated during demolition and excavation activities (Carrasco, 2021).

The study conducted by Huamaní Peralta and Quispe Mamani (2024) quantified the total ecological footprint of a Peruvian university through surveys, resulting in an estimate of 1172.06 GHA/year and 4721.20 t CO_2, associated with energy consumption, mobility and institutional activities. It should be noted that no previous studies are currently available at the local level, indicating a significant knowledge gap.

In the specific case of solid waste, ecological footprint encompasses multiple dimensions, including: waste composition, volume and generation intensity; impacts on biodiversity; greenhouse gas emissions, particularly methane; soil and water contamination; raw material consumption; and the need for technologies and innovations aimed at waste valorization and recycling (Huamaní Peralta and Quispe Mamani, 2024). It further incorporates community participation, environmental education and the implementation of circular economy practices as mechanisms for reducing the overall environmental impact of waste, and constitutes a key tool for promoting sustainable development by facilitating analysis of lifestyles, consumption patterns and their relationship with environmental quality (Chen and Pao, 2024; Huamaní Peralta and Quispe Mamani, 2024; Oo *et al*., 2024). In this regard, the calculation of ecological footprint is particularly relevant when examining factors such as energy consumption, mobility and waste generation, which commonly constitute the principal sources of environmental impact (Chen and Pao, 2024; Ferrante *et al*., 2025).

The main causes of increased ecological footprint are associated with the Industrial Revolution, large-scale production, intensive industrialization processes, population growth and neoliberal economic models (Huamaní Peralta and Quispe Mamani, 2024). Among the consequences are unequal resource appropriation, ecosystem and species loss, the expansion of environmentally unsustainable cities, resource depletion, accelerated climate change, overexploitation and ecological imbalance (Huamaní Peralta and Quispe Mamani, 2024).

From a regulatory perspective, this study is grounded in the Political Constitution of Peru, the General Environmental Law (Law No. 28611), Legislative Decree No. 1278 and its provisions related to integrated solid waste management, and Law No. 29419 and its provisions, which call for the formalization of waste pickers and their integration into municipal solid waste management systems. In addition, this study considers complementary regulations and public policy instruments promoted by the Ministry of the Environment (MINAM) in order to strengthen source segregation, selective collection, recycling and the reduction of single-use plastic consumption. At the local level, the study takes into account the Organic Law of Municipalities, the Integrated Solid Waste Management Plan (PIGARS; *Plan Integral de Gestión Ambiental de Residuos Sólidos*) in Tacna, and municipal ordinances governing source segregation and selective collection programs for household solid waste.

Within this context, the aim of this study was to evaluate the ecological footprint associated with recyclable municipal solid waste in the province of Tacna using official records from the Solid Waste Management Information System (SIGERSOL) and an estimation model based on embodied energy. In addition, the temporal and multivariate dynamics of the main recyclable waste subtypes were examined in order to identify the materials with the greatest relative contribution to the ecological pressure of the municipal system. The results identified fine paper, cardboard and HDPE as the fractions with the highest ecological burden, clearly differentiated from the remaining evaluated materials. These findings support the use of the measurement of ecological footprint as a technical tool for identifying critical fractions and guiding environmental management strategies in municipal solid waste systems. Rather than proposing a new calculation method, the contribution of this study is applied and integrative. To the best of the authors' knowledge, it represents the first multi-year application of the Wackernagel and Rees/Doménech ecological footprint model to official subtype-disaggregated municipal solid waste records from the Solid Waste Management Information System (SIGERSOL) for Tacna, a border city whose intense commercial activity and sustained influx of international visitors generate waste-generation patterns of particular relevance in terms of environmental management. This approach is further strengthened through the integration of multivariate techniques, including principal component analysis and hierarchical clustering, in order to identify structurally similar groups of recyclable materials. By combining these methods, the study addresses a documented local knowledge gap (Section 1) and provides a replicable diagnostic methodology for other Peruvian municipalities with access to SIGERSOL records. Its application is particularly relevant in the Peruvian context, where high levels of informality in the recovery and commercialization of recyclable materials persist despite national policies and programs promoted by the Ministry of the Environment with the aim of strengthening source segregation, selective collection and recycling. In this setting, the proposed methodology provides an objective decision-support tool for identifying the waste fractions that exert the greatest ecological pressure, prioritizing management actions and supporting evidence-based municipal solid waste planning.

2. Materials and methods

2.1. Research design and scope

An applied study was conducted using a quantitative and descriptive approach in accordance with a non-experimental longitudinal design (Hernández-Sampieri and Mendoza, 2018). The research focused on estimating the environmental pressure exerted by the generation of municipal solid waste (MSW) in the Tacna district, Peru, using the Ecological Footprint indicator as a sustainability metric. The study area was the Tacna district (92,972 inhabitants), the capital of the province of the same name. The Tacna district was selected as the exclusive site for analysis, over other districts in the region, due to the integrity and continuity of its historical records. An inclusion criterion based on the completeness of the reports was applied. Statistical processing was performed using R version 4.5.3.

2.2. Information sources and quality control

Data regarding the physical and volumetric composition of MSW were obtained from the Solid Waste Management Information System (SIGERSOL) and the Ministry of the Environment (MINAM). To ensure international validity and study replicability, the information was cross-checked against the annual technical reports issued by the district municipality, thereby ensuring that the input data complied with governmental auditing standards.

2.3. Mathematical model of the ecological footprint (EF)

The estimation of the bioproductive area required to assimilate the fossil energy embodied in MSW was based on the model proposed by Wackernagel and Rees (1998) and adapted by Doménech (2010). Four types of municipal solid waste (glass, paper, metals and plastics) were analyzed, disaggregated into 11 subtypes. The glass group included only secondary glass; the paper group comprised fine paper and cardboard; metals included tinplate steel, steel, iron and aluminum; plastics included HDPE, LDPE, PS and PVC. For each subtype, its corresponding ecological footprint was estimated and the total ecological footprint was subsequently obtained through the aggregation of individual values by waste type.

For the estimation of ecological footprint, the methodology developed by Wackernagel and Rees (1998) and collaborators was employed, which was adapted by Doménech (2010) to the context of solid waste management.

$$\mathrm{EF}=E_{recovered}\, x\, \frac{Annual\ Consumption\ [GJ\ yr^{-1}]}{Energy\ Productivity\ [GJ\ ha\text{-}1\ yr\text{-}1]}\, x\, f_{eq} \quad \text{eq. 1}$$

Where EF represents the ecological footprint, C_{annual} the annual waste consumption (GJ/year), E_{prod} the energy productivity, corresponding to 71 GJ/ha/year for fossil fuels, and f_{eq} the equivalence factor. The main model was developed under a conservative scenario without correction for material recovery (E_{rec}= 1), incorporating the total energy associated with municipal solid waste. This approach avoided the introduction of uncertainty associated with the heterogeneity of waste streams and the limited traceability of material recovery in the administrative records reported by SIGERSOL. A constant equivalence factor of 1.13868813 corresponding to fossil energy was adopted, in accordance with the methodology proposed by Doménech (2010) for the conversion of energy units into ecological footprint units.

It should be noted that the value of 71 GJ/ha/year used for E_prod is not a site-specific estimate of the carbon fixation capacity of the Tacna district; rather, it corresponds to the standard energy productivity of fossil-energy land established by the original Wackernagel and Rees (1998) methodology, and subsequently adopted by Doménech (2010), for converting embodied energy into ecological footprint units, so that the results remained comparable with other studies that have applied the same accounting framework (Huamaní Peralta and Quispe Mamani, 2024; Özdamar and Yiğit, 2026). Replacing this parameter with a locally measured carbon fixation rate would require primary field data for the Tacna area (e.g., forest inventories or soil carbon flux measurements) that are not currently available. Gathering such data would be valuable not only for refining this model's productivity parameter, but also as a basis for future territorial-scale studies that could meaningfully incorporate local biocapacity assessments —an analysis that lies outside the sector-specific scope of the ecological footprint estimated in this study (see Study Limitations). For reference, and for comparability purposes only, Peru's national ecological footprint has been estimated at approximately 1.46-1.54 GHA/person, against a global average biocapacity of approximately 1.80 GHA/person (Huamaní Peralta and Quispe Mamani, 2024). This national-level benchmark contextualizes, without directly substituting, the fossil-energy productivity parameter used in the present model.

It is important to distinguish the ecological footprint estimated in this study from corporate ecological footprint. The present study employed a sector-specific ecological footprint with territorial reference, representing the municipal solid waste management system of the district. Therefore, the estimates obtained should be interpreted as a diagnosis of the municipal solid waste management system as a whole, rather than as the environmental footprint of an individual company or institution.

The organic fraction of municipal solid waste was excluded from the ecological footprint estimation and assigned a value of zero, following the methodological assumption of Doménech (2010), which considers a 100% recovery rate for organic waste through composting. Accordingly, the non-recovered fraction is zero and does not contribute to the ecological footprint calculated using this methodology. This approach does not imply that organic waste is environmentally neutral or that its generation and management have no environmental impacts. Although paper and cardboard are materials of organic origin, they were classified as part of the dry recyclable fraction because their recovery is based on material recycling, rather than on composting, consistent with the waste classification framework applied by the Ministry of the Environment (MINAM). Therefore, the ecological footprint estimated in this study corresponds exclusively to the dry recyclable fraction (glass, paper, metals and plastics) and does not represent the total ecological footprint associated with municipal solid waste.

3. Results

The baseline characterization of the ecological footprint associated with municipal solid waste (MSW) in the Tacna district revealed distinct temporal dynamics and compositions between 2020 and 2024 (Table 1). During the 2020-2023 period, most waste streams exhibited strict stability with minor interannual fluctuations, driven by a baseline demographic trend. However, the year 2024 marked a major shift in the environmental burden structure. Cellulosic materials and specific plastics became the primary drivers of the footprint expansion; cardboard grew sharply from 275.34 GHA in 2023 to 429.66 GHA in 2024, while High-Density Polyethylene (HDPE) rose from 252.81 GHA to 396.07 GHA (Table 1). Conversely, significant reductions were recorded in 2024 for fine paper, Low-Density Polyethylene (LDPE), and polystyrene (PS), with iron exhibiting the most abrupt collapse, falling from 39.03 GHA to 3.74 GHA.

Table 1. Ecological footprint of municipal solid waste (MSW) subtypes in the Tacna district (2020-2024)

Ecological Footprint of MSW						
MSW		Year				
Type	**Subtype**	**2020**	**2021**	**2022**	**2023**	**2024**
Glass	Glass	81.79	82.48	83.08	82.19	59.38
Metal	Tinplate	229.61	231.56	233.25	230.76	215.69
	Steel	1.39	1.40	1.41	1.39	6.77
	Iron	38.84	39.16	39.45	39.03	3.74
	Aluminum	107.02	107.91	108.71	107.54	127.60
Paper	Fine paper	426.42	430.03	433.16	428.55	349.27
	Cardboard	273.97	276.3	278.31	275.34	429.66
Plastic	HDPE	251.56	253.68	255.53	252.81	396.07
	LDPE	172.55	174.02	175.28	173.42	75.98
	PS	86.49	87.23	87.87	86.92	38.78
	PVC	13.32	13.43	13.53	13.38	17.32

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Temporal monitoring of the environmental burden from segregated recyclable waste streams confirmed that the paper fraction dominated the total ecological footprint throughout the 2020-2024 period (Figure 1). This category exhibited a baseline plateau of approximately 700 GHA between 2020 and 2023, followed by a sharp expansion in 2024, approaching nearly 800 GHA. In contrast, plastics displayed a highly stable, linear behavior with negligible interannual variability, consolidated as the second-largest contributor at a constant level of roughly 530 GHA. The lowest environmental pressures were recorded for metals and glass; metals experienced a slight contraction in 2024, dropping below 360 GHA, while glass consistently generated the lowest ecological footprint values, concluding the evaluated period with a pronounced reduction in the final year (Figure 1).

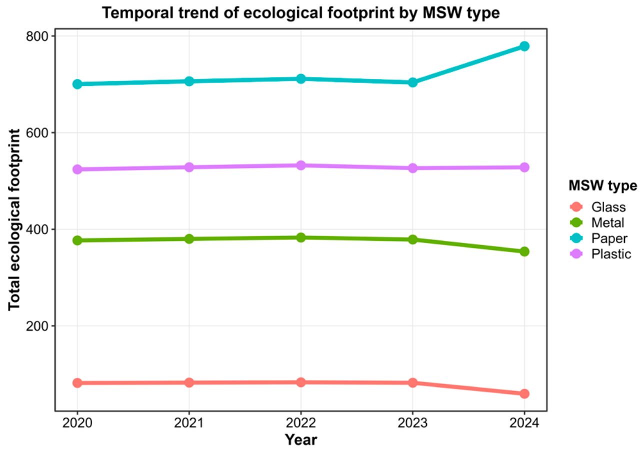

Figure 1. Temporal trend of the ecological footprint by municipal solid waste (MSW) type in the Tacna district (2020-2024)

At a sub-material level, the evaluated streams exhibited highly differentiated temporal behaviors, with a clear structural inflection point occurring in 2024 (Figure 2). Cardboard and HDPE emerged as the primary drivers of growth, showing a sharp expansion from their baseline values to reach their historical peaks of approximately 429.66 GHA and 396.07 GHA, respectively. Moderate increases were also recorded for aluminum, which rose to nearly 127.60 GHA, and PVC, which moved from a baseline of ~13.38 GHA to 17.32 GHA. Conversely, a substantial contraction in environmental pressure was observed across multiple subtypes in 2024. This trend was particularly pronounced for iron, which collapsed from 39.03 GHA to 3.74 GHA, and PS, which fell below 39 GHA. Significant reductions were also registered for LDPE (dropping to ~75.98 GHA), fine paper and glass. Finally, tinplate exhibited slight interannual variability, peaking in 2022 (~233.25 GHA) before decreasing to its lowest level of 215.69 GHA in 2024 (Figure 2).

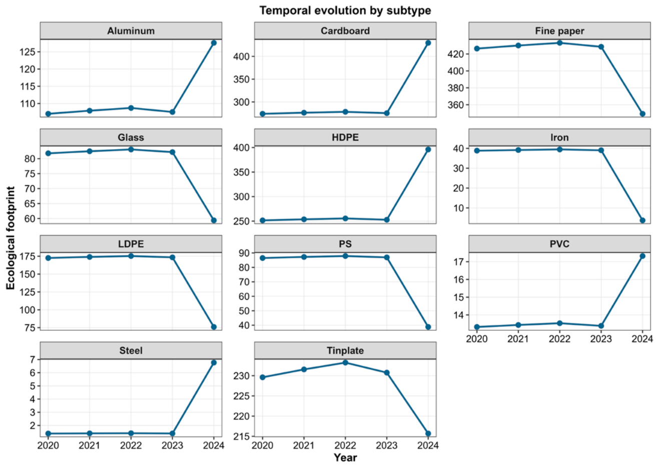

Figure 2. Temporal evolution of the ecological footprint by recyclable waste subtype in the Tacna district (2020-2024)

The matrix-based visualization of the environmental burden highlights distinct intensity clusters across the evaluated timeline (Figure 3). Fine paper maintained a highly intensive footprint block, exceeding 400 GHA during the 2020-2023 period, before attenuating slightly in 2024. Conversely, cardboard and HDPE exhibited a sharp color intensification in 2024, shifting into the maximum footprint threshold (>400 GHA and ~396 GHA, respectively) and demonstrating a synchronized expansion. The lowest relative contributions were systematically registered by steel, PVC and iron, represented within the lowest light-yellow baseline spectrum (<20 GHA for steel and PVC across the time series). Furthermore, the heatmap clearly isolates the generalized footprint contraction of several streams during 2024, where glass, PS, LDPE and iron transitioned into noticeably lighter gradient bands, reflecting abrupt changes in the waste generation dynamics (Figure 3).

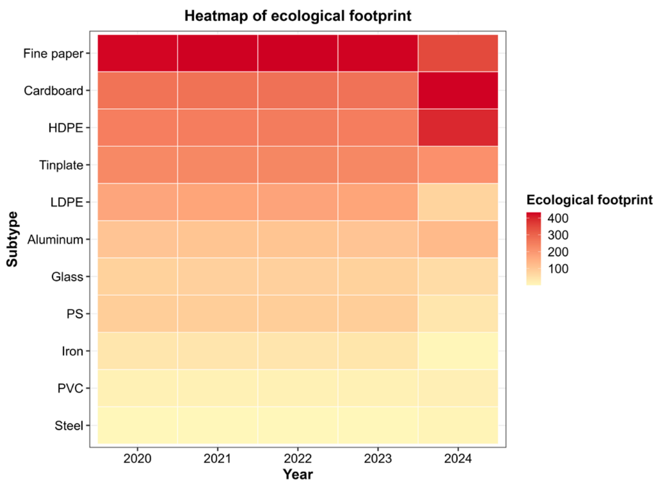

Figure 3. Heatmap of the ecological footprint by recyclable waste subtype in the Tacna district (2020-2024)

Assessment of the mean environmental pressure established a clear hierarchical distribution among the evaluated material streams (Figure 4). Cellulosic components heavily dominated the footprint profile, led by fine paper (~413.5 GHA) and followed by cardboard (~306.72 GHA). Within the polymeric stream, HDPE generated the most substantial burden (~281.9 GHA), markedly outpacing LDPE (~154.3 GHA) and PS. Conversely, the metallic sector displayed fragmented behavior: while tinplate maintained an intermediate mean impact (~228.0 GHA), aluminum remained lower (~112.1 GHA) and iron, PVC and steel consistently exhibited the lowest baseline magnitudes across the entire chronological series.

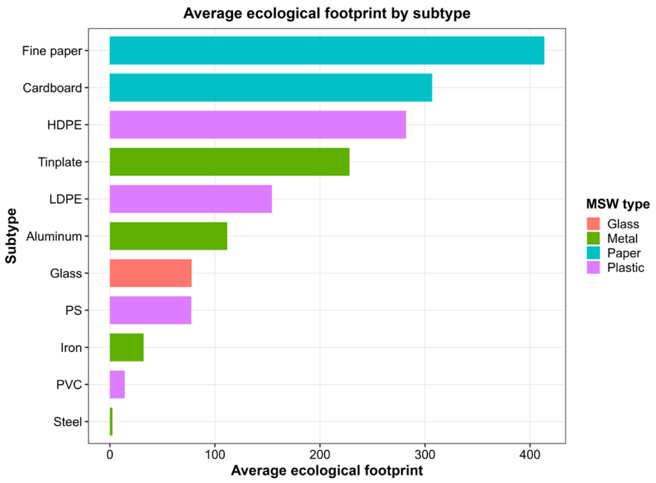

Figure 4. Average ecological footprint by recyclable waste subtype in the Tacna district (2020-2024)

When analyzing the balance during the final year of the time series, the municipal system experienced highly divergent dynamics among its subcategories (Figure 5). A massive relative expansion was isolated in the steel fraction, which surged by nearly 388%. This atypical increase was verified against original SIGERSOL records and municipal technical reports, in order to rule out transcription or reporting errors. This localized growth was accompanied by steady, synchronized growth in the main system drivers, HDPE (~57%) and cardboard (~56%), and stands in sharp contrast to the acute contraction observed in the ferrous and polymeric baselines: iron environmental pressure collapsed by more than 90%, while LDPE and PS dropped by approximately 56% and 55%, respectively, marking a substantial structural reconfiguration of the urban footprint.

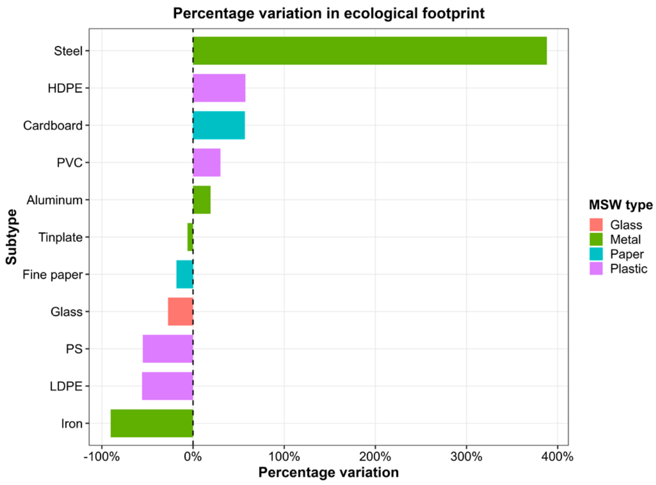

Figure 5. Percentage variation in the ecological footprint by recyclable waste subtype in 2024

The multivariate spatial ordination mapping shown in Figure 6 successfully isolates the structural similarities among the waste subtypes across the monitored timeline. Total variance within the dataset is fully accounted for by the first two dimensions; PC1 exercises an overwhelming dominance at 96.1%, whereas PC2 captures the remaining 3.9%. A stark spatial segregation is evident along the primary axis, where high-impact drivers such as fine paper, cardboard and HDPE form a highly clustered group in the positive quadrants. Conversely, low-footprint subtypes — including steel, iron, PVC, glass and PS— are tightly packed on the negative side, closer to the multivariate origin, confirming their minor and homogeneous contribution to the overall environmental load.

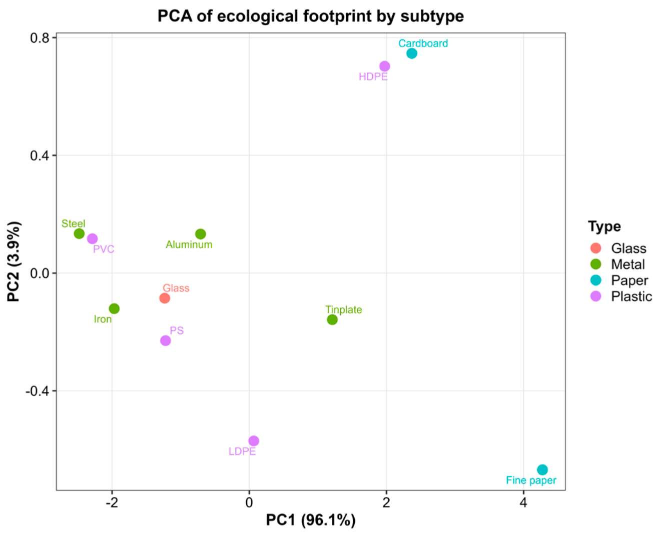

Figure 6. Principal Component Analysis (PCA) of the ecological footprint by municipal solid waste subtype in the Tacna district (2020-2024)

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Hierarchical cluster analysis complemented this spatial distribution by employing Ward's minimum variance method (Ward.D2) on a Euclidean distance matrix, resolving the material matrix into three well-defined categorical groups. As illustrated by the primary bifurcation of the macro-node (Figure 7), a major structural division occurs at an absolute distance threshold of approximately 1,150, separating the critical environmental vectors from the remaining flows. Within this topology, the first cluster (blue box) groups fine paper, cardboard and HDPE, which represent the apex of the ecological footprint structure, with mean values exceeding 300 GHA. An intermediate cluster (green box) links tinplate (mean = 228 GHA) and LDPE (mean = 154 GHA) at a basal linkage distance below 200. Despite belonging to different material categories —metal and plastic, respectively— both subtypes occupy a comparable order of magnitude, which the Ward.D2 variance-minimization criterion resolves as structurally proximate. This cluster is clearly distinct from low-impact residual materials such as steel (1.39-6.77 GHA), which constitute the third cluster (red box), exhibiting high robustness and the shortest internal node heights.

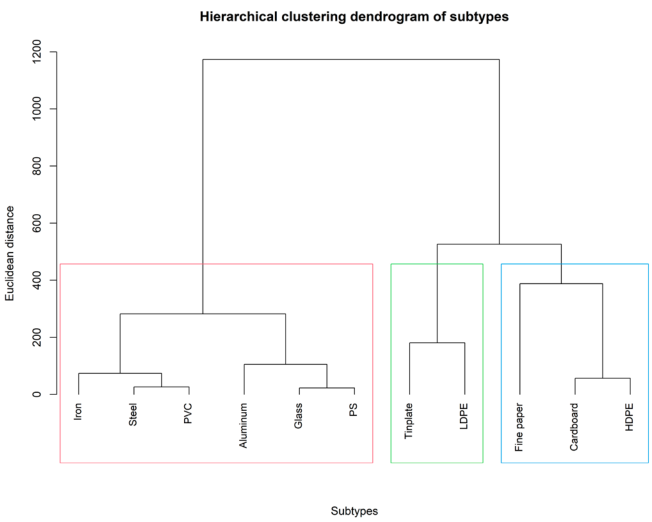

Figure 7. Hierarchical cluster dendrogram (Ward.D2 method, Euclidean distance) of recyclable waste subtypes

4. Discussion

The ecological footprint applied to municipal solid waste constitutes a relevant approach for translating the material and energy pressure exerted by urban management on biocapacity into a comparable metric. In recent studies, ecological footprint has been used to integrate resource consumption, waste generation and territorial sustainability in both cities and institutions, confirming its usefulness as an environmental analysis and policy prioritization tool. In the Peruvian context, recent studies have demonstrated its applicability to university environments and sustainable planning scenarios, reinforcing the relevance of extending this framework to the analysis of municipal solid waste in Tacna (Huamaní Peralta y Quispe Mamani, 2024; Ospina-Mateus *et al.*, 2023; Özdamar and Yiğit, 2026). In Latin America, solid waste management continues to be a field characterized by structural gaps, despite the sustained growth of research on circular economy and waste management. Recent literature has shown that circular economy and waste management constitute one of the most studied topics in the region, but also one of the most challenging, due to institutional heterogeneity, limited material valorization and the persistence of linear disposal models (Ubillús-Farfán *et al.*, 2024). Furthermore, recent reviews focused on Latin America and the Caribbean emphasize that the management of the organic fraction remains a critical sustainability issue, whereas other reviews have highlighted waste reduction, recyclability and public-private coordination as recurrent strategies (Ospina-Mateus *et al.*, 2023; Ubillús-Farfán *et al.*, 2024; Ulloa-Murillo *et al.*, 2022).

The results obtained for Tacna indicate that fine paper, cardboard and HDPE account for the greatest contributions to ecological footprint, which is consistent with recent evidence regarding the relevance of paper, cardboard and plastic waste within recoverable urban waste streams (Lepota *et al.*, 2025; Milbrandt *et al.*, 2024). In a recent characterization of municipal waste, the organic fraction was dominant, but the main recyclable materials identified were paper/cardboard, plastics and glass, confirming that these fractions maintain a significant structural role within municipal systems. In particular, studies focusing on paper and cardboard indicate that these materials constitute a critical fraction for waste reduction and the development of recovery- and recycling-based solutions, whereas recent analyses focused on plastics suggest that their treatment and recycling decisively influence the environmental performance of waste management systems (Lepota *et al.*, 2025; Milbrandt *et al.*, 2024; Zhang *et al.*, 2024).

The large amounts of fine paper and cardboard observed as part of this study are consistent with their heavy use in urban contexts associated with commerce, packaging and institutional and household consumption. Recent literature has shown that these materials require priority attention, because their availability as recoverable waste is high and their utilization leads to relevant environmental and market effects. In Tacna, the greater footprint associated with fine paper suggests that, even when this fraction is recoverable, its contribution to ecological accounting remains considerable, which coincides with the findings of national and international studies that have identified paper and cardboard as among the most relevant components in the structuring of municipal recyclable material flows (Lepota *et al.*, 2025; Milbrandt *et al.*, 2024; Özdamar and Yiğit, 2026). The environmental impact of HDPE also warrants particular attention. Recent evidence on urban waste management and source segregation has shown that plastic recovery can substantially modify the emissions balance and footprint associated with the overall system, and that plastics play a decisive role in treatment systems based on incineration or material recovery. Consequently, the relative increase in HDPE observed in Tacna during 2024 can be interpreted as an indication of changes in the composition of the recovered waste stream, segregation efficiency or administrative traceability of waste, rather than as an isolated increase in the presence of the material itself. According to the literature, in urban systems where source segregation is improved, substantial reductions in the climatic impact of waste management occur, as a result of the recovery of recyclable materials and the reduction of final waste disposal (Zhang *et al*., 2024).

In contrast, glass, steel, iron, PVC and other metallic subtypes exhibited lower or intermediate contributions. This is consistent with recent literature indicating that the reduction of environmental impacts in the waste sector is strongly dependent upon the existence of material recovery circuits and the quality of source separation. When these circuits operate adequately, waste management can shift from being a net source of emissions to a system with significant energy and material recovery; in some scenarios, the entire system may even approach a favorable net balance when recyclable valorization offsets emissions associated with collection and transportation (Oo *et al*., 2024; Zhang *et al*., 2024). Therefore, the lower contributions of glass and metals identified in Tacna should not be interpreted as environmentally irrelevant, but rather as a combination of lower relative volume and more favorable valorization characteristics, compared with other fractions.

The temporal variation observed in 2024, particularly the increase in cardboard and HDPE and the reduction of other fractions, is noteworthy and could be the result of multiple factors. One such potential factor is economic in nature, in line with the findings of Cehlár *et al*. (2025), who identified household income and access to selective collection as determinants of municipal recycling performance. This possibility warrants closer examination of consumption trends within the population and the emerging dynamics of the city. This pattern may also reflect new trends in product packaging —such as the growing use of cardboard boxes linked to the expansion of e-commerce and HDPE containers for detergents, shampoos, yogurts and similar products— consistent with recent evidence that has documented how these shifts in packaging formats are reshaping the composition of urban waste (Syed Ali *et al*., 2024). In this sense, recycling not only enables measurement of the ecological pressure experienced by a system, but also serves as a tool for identifying emerging trends in solid waste generation. Independently of which mechanism is eventually shown to be dominant, the convergence between the descriptive results, PCA and the hierarchical dendrogram reinforces the notion that fine paper, cardboard and HDPE constitute a group exerting greater ecological pressure, whereas the remaining materials form a set characterized by lower relative contribution and greater internal similarity.

A central methodological aspect is that the organic fraction was treated as zero under the assumptions adopted in the model, which caused the interpretation to focus on dry recyclable materials. However, recent literature from Latin America and other regions has shown that the organic fraction is usually one of the most significant components of municipal waste, with direct implications for methane emissions, composting, biodigestion and biogas capture. Therefore, the zero value should not be interpreted as an absence of organic waste in the city, but rather as a consequence of the methodological criterion employed. For future studies, mass-balance or gravimetric characterization of the organic fraction would improve the accuracy of SIGERSOL-based waste-composition estimates; however, the environmental impact cannot be captured by extending the same ecological footprint accounting framework, since organic waste is defined as having a null footprint under the Wackernagel and Rees/Doménech model, regardless of the quantity characterized. Assessing its actual environmental burden would instead require complementary methodologies, such as carbon-footprint or life-cycle assessment of composting and biogas-capture processes (Lepota *et al*., 2025; Ulloa-Murillo *et al*., 2022; Zhang *et al*., 2024).

Beyond the descriptive and multivariate patterns presented above, these findings can be interpreted through an explanatory framework based on three interacting mechanisms, rather than being viewed solely as descriptive outcomes. Firstly, the socioeconomic dynamics of recycling (including household income, housing density, access to curbside collection or drop-off facilities and the degree of formalization of waste-picker networks) influence the proportion of each material stream that is effectively recovered, sorted and recorded as recyclable, rather than disposed of as mixed waste. These factors have been identified previously as key determinants of municipal recycling performance (Cehlár *et al*., 2025).

Secondly, the physical and energetic properties of the materials themselves help to explain why cellulosic and polymeric fractions dominate the ecological footprint. Fine paper, cardboard and high-density polyethylene (HDPE) combine relatively high embodied energy per unit mass with large material flows associated with urban commerce and packaging. In contrast, metals such as steel and iron exhibit lower embodied energy per unit mass and benefit from well-established, high-value recovery markets, thereby contributing proportionally less to ecological footprint, despite their industrial importance (Milbrandt *et al*., 2024).

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Thirdly, administrative and institutional factors (including the efficiency of source segregation, the consistency of reporting across municipal departments and the traceability of recovered materials within SIGERSOL) influence the extent to which year-to-year variations reflect genuine changes in waste generation, rather than differences in measurement and reporting practices. The convergence of these three mechanisms provides an interpretative framework to explain why fine paper, cardboard and HDPE have consistently been consolidated as the waste fractions exerting the greatest ecological pressure within municipal solid waste management systems. Furthermore, this framework identifies key variables (including household income, selective collection coverage, material-specific embodied energy and administrative traceability) that should be explicitly incorporated into future research, in order to move beyond statistical associations toward causal explanations, and to improve our understanding of the factors driving the ecological pressure associated with recyclable municipal solid waste.

5. Policy implications for municipal solid waste management

The aim of the planning instrument known as PIGARS is to improve the integrated management of municipal solid waste in Tacna, covering the different stages of the system, from waste generation and source segregation, to collection, recovery and final disposal. This integrated approach is consistent with Peru's regulatory framework, which defines solid waste management as encompassing the processes from generation through final disposal and calls for waste minimization, material recovery and appropriate final disposal (*Decreto Legislativo No. 1278; Decreto Supremo No. 014-2017-MINAM*). In this context, the findings of this study do not imply a need to establish independent targets for each material type. Waste generation and composition may vary according to household characteristics, consumption patterns and temporal conditions; therefore, the relative proportions of different fractions may change across distinct sectors and periods. Instead, the SIGERSOL-based results identify the fractions that, within the integrated management system, make the greatest contributions to ecological footprint. In particular, cardboard and HDPE exhibited the highest contributions and increasing trends; therefore, these findings may provide complementary evidence to guide source segregation, selective collection and material recovery strategies within municipal planning.

The formalization and integration of waste pickers also constitute relevant components for improvements in the recovery of recyclable materials. The provisions of Law No. 29419 establish the legal framework for regulating recycling activities and call for the formalization and organization of waste pickers, while Supreme Decree No. 005-2010-MINAM establishes the corresponding implementation regulations. Recent evidence from Latin American recycling systems also indicates that formalization can contribute to the social and institutional integration of waste pickers, although such implementation may face organizational and institutional barriers (Castillo-Ospina *et al*., 2025; Gómez-Maldonado *et al*., 2023). In this context, the strengthening of the participation of waste pickers in the recovery of materials such as cardboard and HDPE has the potential to contribute to improving material recovery, while also generating more traceable information on recovered materials.

Finally, the strengthening of SIGERSOL through standardized subtype-level reporting, improved data traceability and periodic validation against field information would enable a more accurate characterization of changes in waste composition and the evaluation of municipal waste management over time. This information could complement PIGARS revision and evaluation processes by providing quantitative evidence regarding the fractions that are most relevant to the ecological footprint of municipal solid waste in Tacna. This approach is consistent with Peru's national regulatory framework, which emphasizes the need for appropriate management, recovery and information throughout the waste-management chain (*Decreto Legislativo No. 1278; Decreto Supremo No. 014-2017-MINAM*), as well as being consistent with prior evidence related to the design of environmental public policy aimed at reducing ecological footprint in Peruvian municipal contexts (Primo Ordoñez, 2022).

6. Conclusions

The results of this study demonstrate that the ecological footprint of municipal solid waste in Tacna is not a temporally stable phenomenon, but rather a system sensitive to shifts in the production and commercialization patterns of consumer goods: the structural break detected in 2024 (evidenced by the relative substitution of paper bags for plastic packaging in bakery products, and by the widespread use of HDPE containers for detergents and liquid cleaning products) suggests that the composition of municipal waste responds, at least in part, to production- and logistics-driven decisions external to the consumer and beyond the scope of their individual purchasing preferences.

The convergence between the descriptive analysis, the PCA and the hierarchical cluster analysis supports the conclusion that fine paper, cardboard and HDPE constitute the structural core of the municipal ecological footprint in Tacna. Accordingly, any environmental impact reduction strategy in the district must necessarily prioritize these three fractions, in order to achieve a meaningful reduction in the system as a whole.

The synchronized growth in cardboard and HDPE, contrasted with the simultaneous contraction of iron, LDPE and PS, indicates that the municipal ecological footprint may be influenced, in part, by decisions beyond the end user's control (namely, product presentation and distribution formats defined by industry and commerce), and therefore reduction policies should not focus exclusively on consumer behavior, but should instead also address the regulation of materials used throughout the production and retail chain.

This study also concludes that ecological footprint constitutes a valid and applicable metric for the environmental monitoring of municipal waste systems in arid contexts within Latin America, given that it integrates the material pressure of multiple waste fractions into a single indicator and enables temporal and spatial comparability.

Finally, treating the organic fraction as having a net-zero ecological footprint, given its capacity for complete biological degradation (Doménech), validates the chosen methodology. This approach successfully isolates the environmental pressure caused specifically by dry recyclable materials, thereby establishing these fractions as the priority target for intervention as part of municipal waste management in Tacna.

Public policy implications. Within this framework, concrete recommendations for municipal management include prioritizing cardboard and HDPE recovery in source-segregation programs, strengthening SIGERSOL through standardized and validated reporting, and using these findings to update material-specific targets in the district's PIGARS. Advancing these priorities will also be reliant upon the transversal strengthening of household segregation programs and the traceability of recovered materials across the municipal solid waste management chain.

Scientific contribution. This study contributes an empirically validated ecological footprint framework for municipal solid waste in an arid Latin American urban context, built upon records from the Solid Waste Management Information System (SIGERSOL) and the application of embodied energy coefficients (ICE) corresponding to each waste fraction. The combination of descriptive, multivariate (PCA), and hierarchical cluster analyses enabled the identification of a statistically significant structural break in waste composition. The findings indicate that packaging-driven shifts, rather than consumer behavior alone, shape municipal ecological footprint, thus supporting a replicable approach for environmental monitoring in similarly arid settings.

Future research lines. Future studies should extend the time series, in order to confirm the persistence of the 2024 structural break, and replicate this PCA-cluster approach in other arid municipalities, to test its generalizability. Because the ecological footprint estimated here is bound to a sector-specific subsystem of municipal solid waste, a direct comparison against local biocapacity was not undertaken as part of this study. Such a comparison would only be meaningful within a broader, territorial-scale ecological footprint accounting exercise, distinct in scope from the sector-specific approach applied here. Similarly, because the organic fraction is treated as having a null ecological footprint under the Wackernagel and Rees/Doménech accounting framework applied in this study, owing to its capacity for complete biological degradation, its environmental impact cannot be meaningfully captured through this same methodology. Future studies could instead apply complementary approaches specifically suited to this fraction, such as carbon-footprint or life-cycle assessments of organic waste management and composting processes. Also warranted are quantitative explanatory models linking packaging and distribution regulation changes to future structural breaks, together with predictive analyses of waste-composition trends, along with the incorporation of direct gravimetric waste-composition data, in order to validate SIGERSOL-based estimates and evaluations of specific policy interventions, such as extended producer responsibility.

7. Study limitations

Data limitations. The analysis relied exclusively on records reported through SIGERSOL, and therefore its accuracy is contingent on the completeness and consistency of municipal reporting. Potential administrative variations in data registration across years and departments cannot be entirely ruled out.

Methodological limitations. The organic fraction was excluded from the ecological footprint estimation and treated as zero under the assumptions of the applied model (see Materials and methods), which restricted the scope of the results to dry recyclable materials. In addition, the study applied the Doménech (2010) adaptation of the Wackernagel and Rees (1998) model, together with the standard fossil-energy productivity parameter (71 GJ/ha/year), which was not a site-specific estimate for the Tacna district, but rather a conventional value adopted for comparability with other studies that have applied the same accounting framework.

Comparability limitations. The ecological footprint estimated in this study represents a sector-specific subsystem of municipal solid waste management, whereas biocapacity indicators refer to territorial-scale ecological systems. Therefore, direct comparison between the two metrics was not conducted, and the results should not be interpreted as a measure of ecological overshoot relative to the biocapacity of the Tacna district.

Interpretive limitations. The explanations proposed for the structural changes observed in 2024, including the three-mechanism explanatory framework discussed

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above, were based on plausible hypotheses grounded in the descriptive and multivariate evidence, rather than on statistically or causally verified relationships, and should be interpreted accordingly. Furthermore, comparative studies cited from the European Union, India, China and South Africa were used as conceptual and comparative references illustrating broader patterns in waste composition and recovery dynamics, rather than as direct evidence of local recycling behavior in Tacna.

Authors' contributions

Freddy Eddinson Ninaja-Zegarra: Formal analysis, investigation, data curation, visualization, writing (original draft), writing (revision & editing).

Karen Brenda Maquera-Loza: Conceptualization, methodology, validation, investigation, data curation, resources, writing (original draft), writing (revision & editing), supervision, project administration.

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Conflicts of interest

The authors declare that they have no financial, institutional or personal conflicts of interest that could have influenced the results or interpretation of this study.

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