Cleaner Waste Systems 10 (2025) 100217

Contents lists available at ScienceDirect

Cleaner Waste Systems

journal homepage: www.journals.elsevier.com/cleaner-waste-systems

Invisible Green Guardians: A long-term study on informal waste pickers' contributions to recycling and the mitigation of greenhouse gas emissions

José Amorim Reis-Filho [a,b,c,*], Jutta Gutberlet [d], Tommaso Giarrizzo [b,c]

[a] Graduate Program in Ecology Applied to Environmental Management, UFBA, Salvador, BA 41180-000, Brazil
[b] Instituto de Ciências do Mar (LABOMAR), Universidade Federal do Ceará (UFC), Abolição Avenue, Fortaleza 3207, Brazil
[c] Núcleo de Ecologia Aquática, Universidade Federal do Pará, Belém, Brazil
[d] Department of Geography, University of Victoria, Victoria, BC, Canada

ARTICLE INFO

Keywords:
Informal waste pickers
Recycling
Greenhouse gas emissions
Urban waste management
Climate change mitigation

ABSTRACT

Recycling plays a crucial role in the circular economy by reintroducing materials into the supply chain. However, certain aspects of the recycling chain, such as the role of informal waste pickers remain underappreciated, despite their significant impact on energy savings and CO_2 recovery. This study investigates the contribution of informal waste pickers to the recovery of recyclable solid waste in Salvador, one of the largest cities in South America, over a 13-year period. Using data from pre-recycling centers that exclusively handle materials collected by waste pickers, we tracked the temporal impact of their activities in diverting solid waste from landfills. From 2010–2022, waste pickers recovered approximately 5700 tonnes of recyclable solid waste, preventing an estimated 27,100 tonnes of CO_2 emissions through material substitution and landfill diversion. The most recovered materials were PET, aluminum, and paper/cardboard, with a notable shift toward increased aluminum recovery. Aluminum and PET contributed most to avoided emissions, with aluminum surpassing PET in recent years. This study underscores the critical yet often undervalued role of informal waste pickers in municipal solid waste management (MSWM) and their contribution to greenhouse gas emission reductions. Given the global prevalence of waste pickers, particularly in low- and middle-income countries, further research on this topic could significantly enhance awareness of the benefits derived from their labor. Recognizing and integrating informal waste pickers into formal waste management systems could strengthen sustainability initiatives in cities and enhance climate change mitigation strategies under dynamic needs of urban populations.

1. Introduction

Rapid human population growth, escalating urbanization, and enhanced living standards have precipitated a significant surge in solid waste production, rendering waste management one of the paramount challenges facing the contemporary world (Wilson et al., 2006; Chabuk et al., 2015; Voukkali et al., 2024). Notably, a fundamental obstacle confronting environmental pollution control, particularly in solid waste management, lies in the insufficient governmental capacity for environmental stewardship (Kain et al., 2022). This inadequacy has led to a lack of coordination among pertinent institutions and actors, resulting in ineffective waste management practices (Taghipour et al., 2016).

In economically developing countries, municipal solid waste management (MSWM) poses a significant challenge, influenced by the daily consumption habits and income levels of citizens. Higher income often correlates with increased access to resources, leading to a rise in the volume of waste generated (Voukkali et al., 2024). Conversely, informal actors operating within the waste chain, such as waste pickers, are frequently marginalized and receive minimal attention from waste management authorities (Barford and Ahmad, 2021; Dean and Asen, 2024). Globally, waste pickers play a crucial role in salvaging a diverse array of materials from household waste, encompassing paper, cardboard, plastics, metals, glass, wood, and occasionally specialized materials like cooking oil, fluorescent lamps, batteries, and electric waste (Wilson et al. 2006; Arora, 2022, Kain et al., 2022). The workforce of waste pickers, particularly in low- and middle-income countries also known as Global South countries (i.e., Africa, Asia, and Latin America nations) which are shaped by historical colonialism, economic inequality, and ongoing development challenges, is extensive and plays a critical role in addressing the gaps in waste collection and recycling

* Correspondence to: Graduate Program in Ecology Applied to Environmental Management, UFBA, Salvador, BA 41180-000, Brazil.
E-mail addresses: josef@ufba.br, amorim_agua@yahoo.com.br (J.A. Reis-Filho).

https://doi.org/10.1016/j.clwas.2025.100217
Received 23 November 2024; Received in revised form 21 January 2025; Accepted 23 January 2025
Available online 28 January 2025

services often left unaddressed by urban management systems (Gutberlet et al., 2017; EIU, 2017).

Solid waste pollution in countries with developing or poor economic conditions is a multifaceted issue, stemming from limited infrastructure, inadequate waste collection services, resource constraints, pervasive poverty, and social exclusion (Brooks et al., 2018, Kain et al. 2022). These challenges lead to high rates of mismanaged and uncontrolled solid waste disposal. However, it is precisely in this region of the planet (i.e., the Global South) that an estimated 15–20 million predominantly informal workers, such as waste pickers, are actively engaged in collecting and diverting waste, thereby providing essential public and environmental services (Gutberlet, 2023). In many countries, the only form of waste recycling rides on the work of informal waste pickers (Cook and Velis, 2020). This labor force comprises some of the most impoverished and marginalized individuals who rely on recyclables for their survival, underscoring the urgent need for action to address this unprecedented social and environmental challenge (Kain et al., 2022; Gutberlet, 2023). Furthermore, in low- and middle-income countries, waste pickers underpin the recycling loop of the circular economy (Barford and Ahmad, 2021). This includes not only those organized in cooperatives but also informal workers, as evidenced in cities in Brazil and Indonesia (Colombijn and Morbidini, 2017). Indeed, waste pickers, while collecting, transporting, and processing waste to earn their livelihoods, also make a significant contribution to reducing the carbon footprint of cities (Mitlin, 2008; King and Gutberlet, 2013). By diverting solid recyclable waste that would otherwise end up in landfills, dumps, incinerators, or open burning, waste picker activities create employment opportunities and income while reducing greenhouse gas (GHG) emissions (Morais et al., 2022).

The process of waste decomposition releases GHGs, commonly referred to in the literature as CO_2 equivalents (CO_2-eq.), which contribute to climate change (King and Gutberlet, 2013). The municipal solid waste (MSW) generated by households is considered the third largest anthropogenic source of methane (CH_4) emissions, constituting 11 % of all global CH_4 emissions (Singh et al., 2018). The reclamation of recyclable materials by waste pickers plays a crucial role in mitigating climate change by curbing GHG emissions and conserving energy (Gutberlet and Danoso, 2015; King et al., 2016). Furthermore, this practice reduces the demand for extracting virgin natural resources to manufacture new goods (Morais et al., 2022) and simultaneously extends the operational lifespan of sanitary landfills (Paul et al., 2012). Despite these environmental benefits, waste pickers remain unrewarded for their important role in providing climate and environmental services (da Silva et al., 2022; Dean and Asen, 2024).

In Brazil, approximately 30 % of waste pickers are organized into associations and cooperatives (Mesquita et al., 2023). These waste picker cooperatives play a pivotal role in the recycling process, fostering circularity, and simultaneously contribute to livelihood support and improved working conditions (Gutberlet et al., 2017; Colombijn and Morbidini, 2017). Within the Brazilian context, recycling efforts facilitated by waste picker cooperatives have yielded significant reductions in GHG emissions (Pimenteira et al., 2004; King and Gutberlet, 2013; Mesquita et al., 2023). However, in most Brazilian cities, selective waste collection services only cover a fraction of the urban area (Gutberlet et al., 2020), likely excluding the contributions of informal waste picker activities. Consequently, the extent of the quantitative contribution of informal waste pickers to GHG emissions reduction remains poorly understood. By recognizing and supporting informal waste pickers, policymakers and stakeholders can harness their potential to further enhance recycling efforts and mitigate climate change impacts.

This paper presents the most comprehensive long-term analysis to date of selective waste collection by independent waste pickers in a major South American city, emphasizing the importance of extended temporal studies in accurately assessing their contributions to recycling and GHG emission reductions. These waste pickers are typically homeless or live under extreme social conditions and are not affiliated with cooperatives, associations, networks, or community-based organizations. Our objective is to understand how these waste pickers contribute to urban waste removal and GHG emission mitigation, shedding light on the environmental and social benefits of their activity. Our findings are based on a monthly monitoring conducted over thirteen years as part of a larger research project, focusing on recycling centers specialized in receiving materials from waste pickers. Despite the outcry against solid waste, and subsequent corporate commitments to material recycling (UNEP, 2013), we argue that there has been greater action on material flows than in support of the people who move these flows (Barford and Ahmad, 2021).

2. Methodology

2.1. Brazilian scenario of selective collection

In 2021, 1567 Brazilian municipalities — representing 28.1 % of all municipalities nationwide (5570) — had some form of formal waste management arrangement. This marks a 6 % decrease compared to the previous year (SNIS, 2021). The diagnosis from the National Sanitation Information System (SNIS) (2021) highlights that selective collection initiatives in Brazil are still in their infancy. The absence of waste separation exacerbates the strain on final disposal systems and accelerates the depletion of natural resources, which are nearing exhaustion in many cases (Guabiroba et al., 2023). As a direct consequence, despite the implementation of the National Solid Waste Policy (PNRS) in 2010 (Federal Law No. 12305/2010), the nationwide formal recovery rate of recyclable materials remains below 3 % (SNIS, 2021). Despite numerous initiatives aimed at promoting the sector and increasing the utilization of recyclable materials, the recovery rates persist at low levels, indicating the inadequacy of selective waste collection systems. In 2021, it was estimated that Brazil recovered 1.12 million metric tons of solid recyclable waste, representing only 5.3 % of the total potential (SNIS, 2021).

2.2. Study location

Salvador, with a population of approximately 2.9 million people and covering an area of around 700 square kilometers, is the fourth most populous city in Brazil and the tenth most populous city in South America. It faces significant challenges in public waste management, particularly in the collection and recycling of materials (Oliveira et al., 2022). The city's formal waste management systems often overlook the substantial contributions of informal waste pickers. As a result, these waste pickers rely on precarious pre-recycling centers (PRCs), which are small, unregulated business hubs functioning as artisanal recycling shops (Fig. S1). These PRCs receive recyclables collected from various informal activities, including mainly those carried out by informal waste pickers. However, according to their owners, waste pickers are the primary suppliers of these PRCs. Although there is no comprehensive census on the number and distribution of PRCs that serve informal waste pickers, this study involved seven PRCs located in populous neighborhoods of Salvador (Fig. S2). Strategically positioned within the communities, the PRCs act as a critical intermediary between waste generators and formal recycling facilities. Equipped with precarious infrastructure, the centers facilitate the segregation of recyclable materials from the general waste stream, such as plastics, glass, metals, and paper that are systematically separated and weighted, thereby optimizing their potential for reprocessing and reuse.

2.3. Informal waste pickers context

Our focus is on the solids waste retrieved by independent and informal waste pickers and pre-recycling centers specialized in receiving the material from this kind of waste worker (Fig. 1). As part of a larger social project conducted by the NGO "Guerreiros da Paz" (https://vol

Fig. 1. Types of activities employed by informal waste pickers in Salvador city, Brazil.

untarios.com.br/entidade/3960) to assist homeless individuals, this study assessed the population of waste pickers supplying PRCs with solid waste. On average, 800 ± 95 waste pickers were responsible for supplying these PRCs annually, which is notably significant compared to previous studies evaluating waste pickers in Salvador city (Marchi and Santana, 2022). Differently of other waste workers, waste pickers usually collect recyclable (and reusable) materials directly from households and other clients, from garbage left in the streets, in or around skips, creeks, drainages, markets, public trade fairs, dumps and on landfills. In Brazil, many waste pickers view their work primarily as a means of subsistence, with only a small number recognizing organized efforts, such as through cooperatives, as a legitimate pathway for social and political participation (Vieira, 2011). Typically, these waste pickers do not participate in formal recycling cooperatives and are often subjected to social stigma, which is used to justify violent oppression and prejudice against them (Kariuki et al., 2019; Yousafzai et al., 2020).

2.4. Solid waste records and estimates of greenhouse gas mitigation

Two strategies were designed to understand how waste pickers contribute to mitigation of GHG emissions in the studied city: Firstly, empirical data on quantities of solid waste stored in each PRC, categorized by type and measured in kilograms, were obtained monthly through internal manager appointments (inventory data) from 2010 to 2022. The PRCs maintain meticulous records of the materials, as the waste is eventually sold and dispatched to final recycling industries for processing. We were careful to obtain data exclusively from waste pickers' contributions, which accounted for 97 % (± 2.5) of the solid waste stored in the PRCs. Therefore, we did not consider other sources of waste supply in our analysis. The types of materials recovered from waste pickers and stored included wood, paper & cardboard (P&C), mixed plastics, PET (polyethylene terephthalate), HDPE (high-density polyethylene), PVC (polyvinyl chloride), LDPE (low-density polyethylene), PP (polypropylene), glass, aluminum, steel, scrap metal, and textiles. These centers function continuously, both during daylight and nighttime hours, within a basic infrastructure and without machinery for handling recyclable materials (Fig. S1). These PRCs operate informally without work records or safety equipment, and without integration into formal reverse logistics projects. Consequently, they often lack essential infrastructure, operate with minimal regulatory oversight and are not remunerated for the environmental service they provide (WIEGO, 2021a,b).

The MSWM system in Salvador does not have a comprehensive and widespread process of solid waste separation before they are sent to landfills, except for some hubs of selective collection that operate irregularly throughout the year and cover only a small fraction of the urban area. This posed a challenge for calculating the baseline emissions of CO_2. Therefore, data on quantities and types of solid waste at municipal landfills were obtained through specific studies conducted in some years (SECIS, 2019), regular municipal solid waste collection (between 2012 and 2014 through the Sustainable Cities Program), institutional reports from ABREMA (https://www.abrema.org.br/), and local news media. In cases where specific data was lacking, we projected quantities of solid waste and types for the years (i.e., baseline scenario) based on gravimetry of solid wastes performed by Caldas (2007), Araújo (2015) and Santos et al. (2023) (see Table S1).

Second, using the amount and types of solid waste recorded from each PRC, we employed the IPCC methodology (IPCC, 2006, 2008), which offers a structured approach for estimating annual GHG emissions originating from various waste treatment processes, including landfilling, incineration, composting, and anaerobic digestion. These guidelines are a well-established methodology for the estimation of emissions of GHGs from waste management practices and have been used extensively by many studies (King and Gutberlet, 2013, Mesquita et al., 2023, Zhu-Barker et al., 2017; Tun and Juchelková, 2019; Beltran-Siñani and Gil, 2021). This methodology additionally enables the calculation of direct GHG avoided emissions associated with recycling activities, a concept first adapted by King and Gutberlet (2013) and then by WIEGO (2021a, 2021b) to enable GHG assessment of inclusive recycling, such as that performed by informal waste pickers. Our analysis specifically accounts for the indirect GHG emissions avoidance resulting from the diversion of recyclable solid waste from landfills upon integration into the recycling chain (Pimenteira et al., 2004). The estimation of GHG emissions from disposal sites takes into account the impact of waste diversion by the informal waste picker sector (Mesquita et al., 2023). Any waste intercepted by informal waste pickers and diverted from disposal sites decreases the overall amount of waste sent for disposal, thereby leading to a reduction in associated emissions (Gichamo and Gökçekus, 2019). The assumption based on the WIEGO (2021) calculation for the baseline scenario, where no recycling occurs, is that approximately 81,900 tonnes of waste and recyclable materials generated by the residents and businesses of Salvador city would be yearly disposed of at the municipal sanitary landfill (Table S1). Additionally, it is assumed that, in this scenario, because these resources were not recycled back into the manufacturing supply chain, 81,900 tonnes of virgin resources were used annually in product fabrication.

The method utilized adheres to Tier 2 guidelines outlined in the IPCC (2006), which incorporate models of waste degradation processes within disposal sites (Gautam and Agrawal, 2021). It is assumed that the peak CH_4 emissions occur in the initial years following waste deposition, gradually declining due to the consumption of degradable organic carbon (DOC) through bacterial decomposition. The quantity of CH_4 emissions from solid waste disposal sites (SWDS) is contingent upon the availability of DOC and fossil carbon (IPCC, 2006). Thus, we assumed that the sorted solid waste recovered by informal waste pickers would directly contribute to the extensive process of extracting virgin raw materials through recycling, avoiding disposal in landfills or open burning, and ultimately leading to a reduction in GHG emissions. The steps involved in calculating CH_4 emissions in a landfill are as follows:

$$CH_4\ \text{Emissions} = [\Sigma\ (CH_4\ \text{generated}_{x.T} - R_T)] * (1 - OX_T) \tag{1}$$

Where CH_4 Emissions = CH_4 emissions emitted in a year T; T = year; x = waste category or type/material; R_T = recovered CH_4 in year T, and OX_T = oxidation factor in year T.

$$DDOC_m = W \times DOC \times DOC_f \times MCF \tag{2}$$

Where $DDOC_m$ = mass of decomposable DOC deposited; W = mass of waste deposited; DOC = degradable organic content in the year of deposition; DOC_f = fraction of DOC that can decompose (fraction), and MCF = CH_4 correction factor for anaerobic decomposition in the year of deposition.

$$L_0 = DDOCm \times F \times 16/12 \tag{3}$$

Where L_0 = CH_4 generation potential; $DDOC_m$ = mass of decomposable DOC deposited; F = fraction of CH_4 in generated landfill gas, and 16/12 = molecular weight ration CH_4/C.

In studies evaluating GHG mitigation, formulas based on CH_4 emissions are employed due to the significant contribution of methane generated from anaerobic decomposition of organic waste in landfills, and results are expressed in terms of CO_2 equivalent (CO_2 eq) to facilitate direct comparison and effective communication of the overall impact on climate change mitigation (Eggleston et al., 2006; Bogner et al., 2007).

Each type of solid waste contains varying amounts of dissolved organic carbon (*DOC*). High *DOC* content in waste indicates the potential for high CH_4 emissions (Singh et al., 2018). The *DOC* values for different waste types monitored in this study were sourced from the IPCC inventory (2006) (Table S2). Another crucial factor in calculating GHG emissions from landfills is the fraction (*F*) of CH_4 emissions. The *F* value determines the proportion of CH_4, and other gases emitted in a landfill (IPCC, 2006). Based on default IPCC values (IPCC, 2006), an *F* value of 50 % was adopted. Additionally, the half-life value of waste must be considered, which is influenced by temperature and precipitation rates. Given Salvador city's tropical climate with temperatures above 28°C and an annual rainfall exceeding 1000 mm, these factors were accounted for in the analysis (Meteoblue, 2024). The specific emission factors used for calculation of GHG avoided emissions are presented in the Supplementary material (Table S3).

2.4.1. *Database caveats*

Our analytical model was limited by a lack of data from PRCs, including information on electricity and water consumption at each center, as well as specific details regarding collection vehicles (such as distance traveled to final recycling factory, fuel consumption, charge capacity, and number of trips). Besides, while there are GHG emissions associated with recycling and landfill diversion activities (King and Gutberlet, 2013), our analysis did not account for these subsequent steps in the waste management chain. Therefore, our assessment may not fully capture the comprehensive GHG mitigation potential of waste picker activities. Nevertheless, we argue that highlighting the benefits of waste removal and GHG mitigation resulting from waste picker activities is crucial to foster and ultimately guide efforts to involve them in MSWM. Consequently, our evaluation focused on the stage at which waste pickers utilize wheelbarrows, improvised trolleys, and predominantly individual collection bags to divert solid waste from public roads and unauthorized dumping grounds (Fig. 1).

2.5. *Data analysis*

The data regarding quantities of solid waste and estimates of GHG emissions avoided were annually organized by material type and tonnes of CO_2 eq/year avoided for descriptive analysis. Subsequently, to examine the yearly relationship between these variables, with a focus on solid waste types, we employed the Mann-Kendall, with the year as the independent variable (Hamed and Ramachandra Rao, 1998). This approach enabled us to quantify the strength and direction of potential relationships.

Given our dataset with monthly measurements of quantities and types of solid waste spanning multiples years, along with yearly estimates of GHG avoided emissions, we used a Generalized Linear Mixed Model (GLMM) to analyze the temporal trends and the impact of different types of retrieved solid wastes on GHG emission reductions, accounting for random effects associated with seasonal variations and potential PRCs differences. This choice was made due to the nested structure of the data, where measurements are nested within months and years, as well as the distribution of responses not being limited to a normal distribution (Gelman and Hill, 2007), so that allows examining how these two processes interact and contribute to overall outcomes.

GLMMs allow for the analysis of non-normally distributed data while accounting for the hierarchical nature of the data structure, making them well-suited for our analytical needs. The GLMM extends the GLM framework by incorporating random effects, making it suitable for analyzing hierarchical or nested structures, such as repeated measures (Barr et al., 2013). In our case, the nested structure arises from months nested within years. We defined solid waste quantities and avoided emissions (tonnes CO_2-eq/year) as the dependent variables and factors such as PRCs, material types, and time (years and month) as independent variables. We included random effects for solid waste types nested years to account for the repeated measures nature of the dataset. Since our dependent variable is likely continuous and non-negative, a gamma distribution was suitable for modeling positively skewed continuous data (Lee and Grimm, 2018). The different types of materials recovered from waste pickers and PRCs represented the random and fixed factors in our model, respectively. Mixed-effects regression models were fitted using the package *lme4* (Bates et al., 2015). The GLMM trees were fitted using package *glmertree* (Zeileis and Fokkema, 2019). To estimate the models' predictive accuracies, we employed 10-fold cross validation. Cross validation provides a more realistic estimate of generation error than calculating variance explained in the training sample (Hastie et al., 2009). Cross-validated predictions for the mixed-effects regression and GLMM tree models were computed based on both random and fixed effects, so that predictions for all fitted models captured the effect of time and material types on quantities of solid waste. Prediction error was quantified as the mean squared difference between predicted and observed response variable values (MSE). All analyses were performed in the R environment (R Core Team, 2022).

3. Results

3.1. Solid waste types, quantities, and temporal trends

Over a period of thirteen years (2010–2022), waste pickers in Salvador city recovered approximately 5770 tonnes of recyclable solid waste, with a yearly average of 443.9 tonnes (± 184). PET packages (57.5 %), aluminium materials (27.7 %), and paper & cardboard (4.7 %) collectively accounted for 5186 tonnes (Fig. 2) and remained along the years as the most retrieved materials (Fig. 3). With the exception of LDPE, aluminum, and steel, all other solid waste materials showed a decreasing temporal trend in retrieval by waste pickers. There was a notable reduction observed for all materials during the COVID-19 pandemic (Fig. 3), including the closure of some pre-recycling centers (Table S3). This decline was followed by a resurgence in collection rates towards the end of 2022, coinciding with the official declaration of the end of the pandemic in Brazil (Fig. 5). The raw data is available in the Supplementary material (Table S4).

3.2. Estimates of GHG mitigation from waste pickers activities

Between 2010 and 2022, the activities of solid waste retrieval performed by waste pickers resulted in the avoidance of GHG emissions, totaling 27,113 tonnes of CO_2, primarily attributed to two processes. Waste collection for recycling, which involved the substitution of virgin raw materials, contributed to the avoidance of 26,229 tonnes of CO_2, while diversion from disposal sites (e.g., landfills and dumps) yielded 884 tonnes of CO_2 avoidance. Over the years, an increasing trend was observed in the first process during the initial years of the temporal series, followed by stabilization, while the second process showed a decreasing trend. Both processes experienced sharp declines during the COVID-19 pandemic years (refer to Fig. 4 for absolute values absolute values, which have been adjusted logarithmically to better illustrate the relative contributions of each process). The raw data and emission factors are available in the Supplementary material (Tables S3 and S5).

The types of recovered materials that made the most significant contributions to GHG emissions avoidance were aluminium (17,911.7 tonnes of CO_2) and PET (7336.7 tonnes of CO_2), followed by scrap metal (344.3 tonnes of CO_2) and paper & cardboard (223.3 tonnes of CO_2). Fig. 5 presents the absolute values, adjusted logarithmically to better illustrate the relative contributions of each material type. Over the years, aluminium and PET remained the main recovered materials contributing to the highest estimates of GHG emissions avoidance, with aluminium showing an increasing trend and PET showing a decreasing trend. However, all solid waste materials, including aluminium and PET, experienced sharp GHG emissions avoidance during the COVID-19 pandemic period (Fig. 6). Analyzing the relationship between the solid waste recovered by waste pickers, which has generated the highest estimates of GHG emission avoidance (i.e., aluminium, PET, scrap metal, and paper & cardboard), our findings show a very high correlation between quantities and GHG avoided emissions (Fig. 7A). However, when examining the ratio between recovered materials (tonnes/year) and GHG emission avoidance estimate (tonnes of CO_2/year), such as aluminium and PET, the relationship appears to be inversely proportional (Fig. 7B).

3.3. Integrating and partitioning of effects of solid waste retrieval and estimates of GHG mitigation

In the GLMM tree analyses, lower p-values within the nodes indicate increased interaction with the decision model. Our analysis identified "year" as the primary partitioning variable, followed by "month" and "pre-recycling center" (PRC) as secondary partitioning variables (Fig. 8). The terminal nodes depicted in Fig. 8 reveal a dual factor-subgroup interaction. Specifically, subsequent splits result in improved outcomes and lower standard error (SE) scores within the "month" node, categorized by solid waste quantities (differentiated by type) and avoided GHG emissions (measured in tonnes CO_2-eq/year), with PET and aluminium exhibiting higher outcomes, followed by paper & cardboard (P&C) and glass. However, within this partitioning node, a trade-off emerges between PET and aluminium in terms of waste quantities (i.e., PET predominates) and avoided emissions (i.e., aluminium predominates) (see Fig. 8 – left panel). Within the pre-recycling center node, the dependent variables (i.e., solid waste quantities and avoided

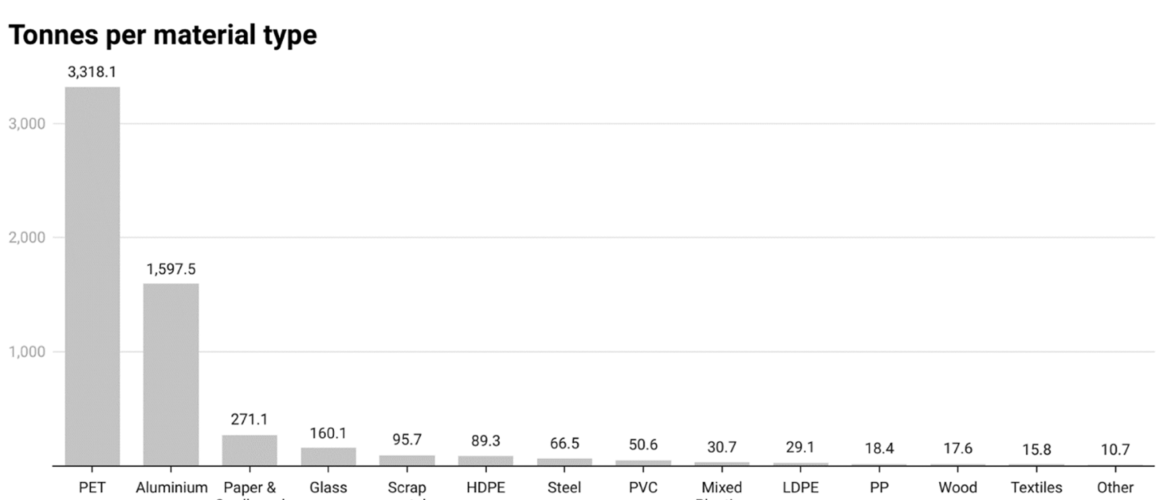

Fig. 2. Total quantities measured in tonnes of solid waste materials retrieved by waste pickers between the years 2010 and 2022.

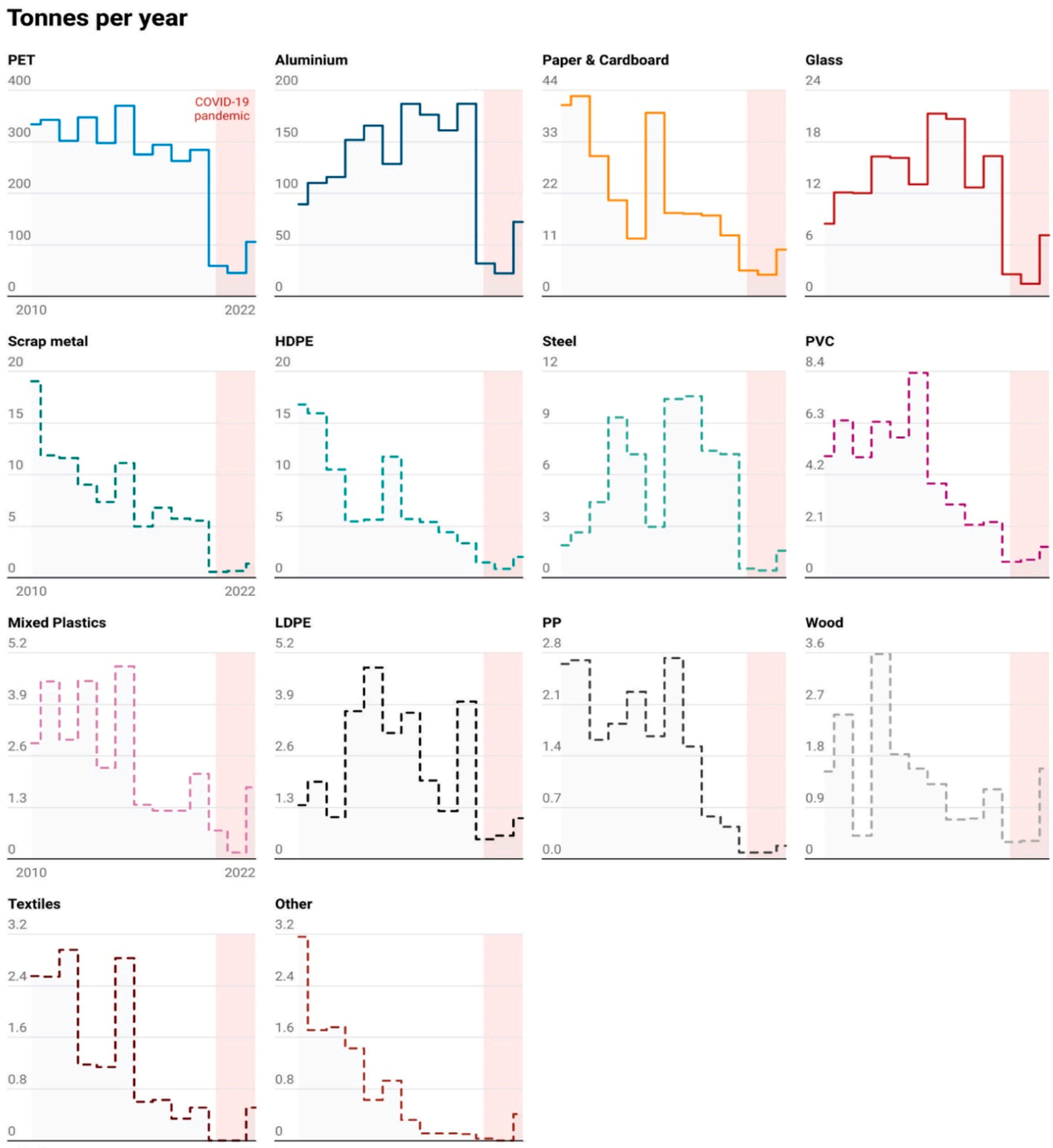

Fig. 3. Yearly variation, measured in tonnes, of solid waste materials with specific quantity scales retrieved by waste pickers between the years 2010 and 2022. The period encompassed by the COVID-19 pandemic is evidenced. Solid lines represent the most abundant retrieved recyclables, while dashed lines represent the second and third most abundant groups of recyclables.

emissions) exhibit lower outcomes and higher SE scores, indicating significantly lower partitioning between treatments (see Fig. 8 – right panel). We extracted coefficients values of the random intercept from the full estimated mixed model and provided different predictions for different solid waste types and their GHG avoided emissions within each leaf of the tree structure. The Fig. S3 shows the ranking of the estimated random-effects confirming that the best outcomes were observed for aluminium, PET, scrap metal, and P&C as the 95 % confidence intervals does not overlap with 0.

Finally, the mixed model analysis revealed a strong association between years and months for a small set of solid waste types that had the highest quantities retrieved by waste picker activities. Additionally, these waste types generated the highest estimates of GHG emissions avoidance. This finding underscores the importance of considering both temporal and material-specific factors when assessing the effectiveness of waste picker activities in mitigating GHG emissions.

4. Discussion

Waste pickers have garnered increasing attention from scholars across various academic disciplines, including environmental and sanitation engineering, political economics, urban anthropology, and urban geography (Morais et al., 2022). However, there has been limited focus on the potential of informal waste pickers' activities in solid waste collection for mitigating GHG emissions (but see Pimenteira et al. 2004; Gutberlet and Danoso, 2015; WIEGO, 2021a, 2021b). In this long-term

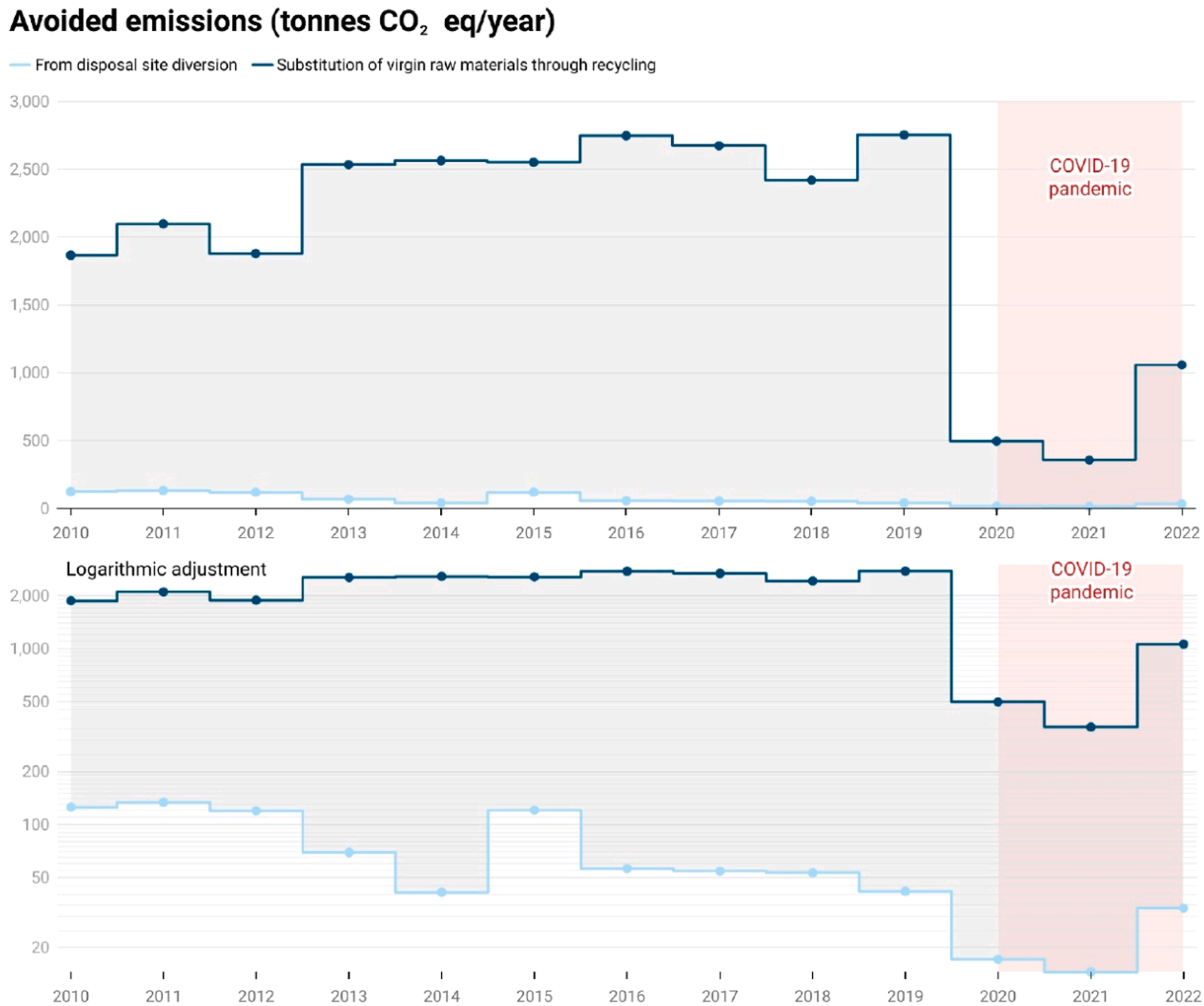

Fig. 4. Estimate of greenhouse gas (GHG) emissions avoidance expressed in tonnes of CO_2-equivalent per year, resulting from the work of waste pickers. The two key processes carried out by waste pickers are the substitution of virgin materials through recycling and the diversion of waste from disposal sites.

study, we have demonstrated the significant impact of waste pickers' activities in retrieving various types of solid waste and contributing to GHG emissions avoidance. This is primarily achieved through diverting materials collected by these informal collectors within the urban landscape, thereby incorporating the waste into the recycling sector. This practice reduces the need for virgin raw materials and minimizes the disposal of waste in conventional sites such as landfills and dumps. Indeed, this study primarily aims to draw attention to the important role of a socially "invisible" and neglected workforce in promoting recycling-related processes. The involvement of informal waste pickers can substantially influence assessments of GHG mitigation within urban environments over prolonged periods, as demonstrated in this study, underscoring the importance of integrating their activities into broader discussions on MSWM and climate change mitigation strategies.

In most cities in the Global South, there are no formal selective waste collection programs, and growing evidence suggests that the informal sector retrieves the majority of recyclable materials (Conceição, 2005; Hartmann, 2012; Chokhandre et al., 2017; EIU, 2017; Kasinja and Tilley, 2018; Kumar et al., 2018; Gutberlet, 2023). Additionally, recognizing their potential to facilitate energy conservation and CO_2 reclamation underscores the importance of including waste picker contributions in such discussions. Furthermore, despite the imperfections and unmanaged nature of waste collection and storage (such as pre-recycling centers), it implies a version of circularity, where waste collection is critical to the recycling loop of the circular economy (Gutberlet et al., 2017; Barford and Ahmad, 2021). This process has already been confirmed in many countries, such as China and India (Medina, 2008), Mexico and Costa Rica (Wilson et al., 2006), and Indonesia (Sembiring and Nitivattananon, 2010).

4.1. *Selective collection by informal waste pickers and GHG mitigation*

Yet, in general, waste pickers represent less than one percent of the urban workforce (International Labour Organization, WIEGO, 2013). Across the Global South, as is the case in Salvador city, waste picker groups share certain common features, often comprising marginalized populations living in extreme poverty (Samson, 2010; Morais et al., 2022). They are frequently among the most vulnerable people in society (Dias, 2016). Job opportunities and means of survival are often limited to peripheral occupations, with waste collection becoming the only alternative (Gutberlet, 2023). Ironically, these individuals survive on unmanaged waste generated by society while contributing to the

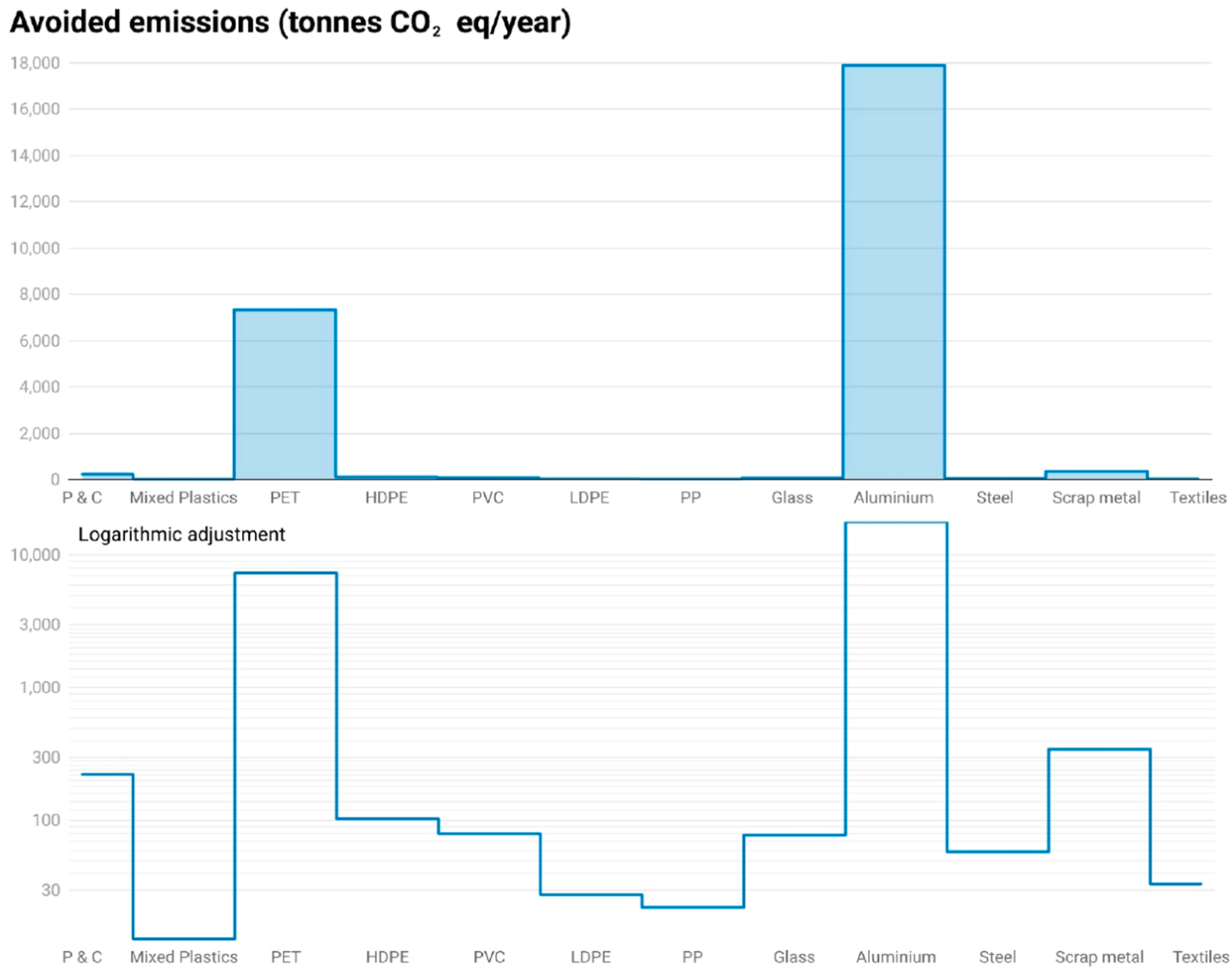

Fig. 5. Total estimate of greenhouse gas (GHG) emissions avoidance expressed in tonnes of CO_2-equivalent per year for solid waste types recovered from the activities of waste pickers between 2010 and 2022.

recycling process and concurrent GHG mitigation. Although the waste picker groups targeted in this study are not formalized, they have made a significant contribution to municipal solid waste management (MSWM). Recognizing and supporting their contributions could help lift many families out of poverty by creating better job opportunities within the MSWM sector (Morais et al., 2022, Zhang et al., 2024). In Salvador, waste pickers retrieved approximately 440 tonnes of recyclable materials annually, with a peak of 599 tonnes in 2015 (see Table S3). Additionally, their activities resulted in an average annual CO_2 emission avoidance of 2068 tonnes, reaching a maximum of 2795 tonnes in 2019 (see Table S5). This amount is particularly significant when compared to formal waste picker cooperatives that have agreements to receive materials from garbage collection services and urban cleaning operations, as well as access to machinery for handling recyclables and transportation vehicles (Pimenteira et al., 2004; King and Gutberlet, 2013; Mesquita et al., 2023).

For instance, Mesquita et al. (2023) found that three waste picker organizations in Brasília, the capital city of Brazil, processed around 2880 tonnes of recyclable material in one year (i.e., 2019), generating approximately 18,030 tonnes of CO_2 emission avoidance. In another study, King and Gutberlet (2013) monitored one recycling cooperative in the metropolitan region of São Paulo, Brazil's largest city, over nearly six months. Their findings revealed a substantial reduction in CO_2 emissions, estimated at 1443 to 2720 tonnes, resulting from recycling activities and the diversion of waste from landfills. Although there is a notable contrast between the cooperative model of waste collection and processing and the more rudimentary approach used by informal waste pickers in Salvador, it is clear that these workers play a significant role in MSWM and GHG mitigation efforts. However, when comparing our findings with other studies, it is imperative to account for variations in GHG calculation methodologies and a broad spectrum of parameters, including energy consumption disparities between the production of virgin materials and recycled resources, transportation logistics, and non-energy-related GHG emissions (Friedrich and Trois, 2013). Despite these differences, our study provides a foundational reference point for integrating the unique aspects of solid waste collection performed by informal waste pickers into future updates of GHG calculation models.

Estimations of GHG emissions mitigation per material type recovered by waste pickers highlighted aluminum and plastics, particularly PET, as the most effective materials in avoiding GHG emissions when substituting virgin resources in manufacturing processes. This observation aligns with findings from previous studies that assessed GHG emissions reduction based on the metric of CO_2-equivalent per tonne of waste material (Chen and Lin, 2008; Damgaard et al., 2009; King and Gutberlet, 2013). Moreover, while recyclable steel materials may offer a greater reduction in CO_2-equivalent emissions per tonne compared to plastics (Damgaard et al., 2009), our results highlight the prominence of plastics, especially PET, among the materials collected by waste pickers

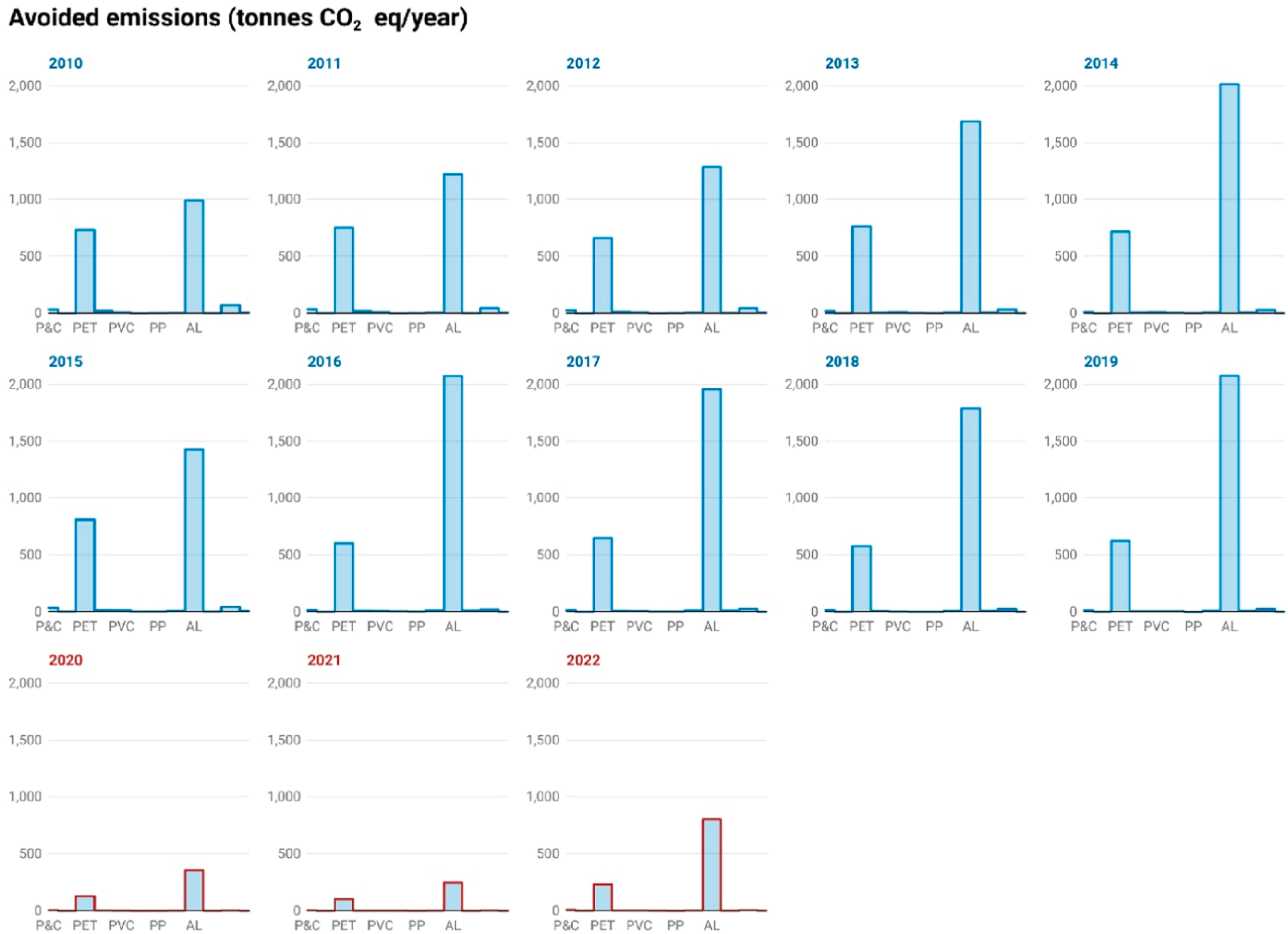

Fig. 6. Total estimate of greenhouse gas (GHG) emissions avoidance expressed in tonnes of CO_2-equivalent per year for solid waste types recovered from the activities of waste pickers, categorized by each year. The period encompassed by the COVID-19 pandemic is highlighted by red borders around the columns in the graph. For a complete visualization of solid waste types on the X-axis, refer to the caption of Fig. 5.

in Salvador, who gather plastic PET in greater abundance than other materials. This preference for plastics stems from the large quantity of PET materials collected in comparison to other materials. These activities primarily involve the collection of refuse left in streets, around dumpsters, in streams, drainage systems, and unregulated dumping sites. It is also crucial to consider the temporal aspect of the relationship between the quantity of each material type recovered by waste pickers and the corresponding estimates of GHG emissions avoidance (as depicted in Fig. 7). This temporal analysis highlights that primarily aluminium and PET, followed by scrap metal, paper and cardboard, consistently contribute to sustained GHG mitigation when diverted from landfills and reintegrated into the recycling chain through the activities of waste pickers. Thus, our results demonstrate the role of waste pickers in GHG emissions mitigation, emphasizing their substantial contributions to reducing emissions associated with aluminium and plastics. However, given that informal waste pickers operate under highly dynamic and variable collection conditions – characterized by absence of productivity targets, unorganized routes for recyclables recovery, and poorly managed pre-recycling centers (see 2.4.1) – it is imperative to consider the specific operational contexts of waste picker populations in each city. This includes accounting for cultural and economic factors that influence their activities.

Between 2010 and 2022, the duration of our study, Salvador city experienced a notable decline in population, amounting to 9.6 % (from 2,657,656 in 2010–2,417,678 in 2022) (IBGE, 2023). This decline is primarily attributed to residents migrating to neighboring localities along the north coast of the state (see Pereira and Fernandes, 2022). It is significant to note that the quantity of solid waste collected by waste pickers, including various materials, declined over time, particularly for high-volume items such as PET, paper and cardboard. This trend was evident before the onset of the COVID-19 pandemic, highlighting the complex relationship between urban population dynamics and solid waste generation (see Singh et al., 2018). While the COVID-19 pandemic has significantly impacted all sectors of the economy, the informal recycling sector has demonstrated some degree of resilience (Tucker and Anantharaman, 2020). Pitoyo et al. (2020) assert that the informal sector serves as a lifeline for individuals who have lost their jobs or income during this macroeconomic crisis. However, our study did not observe this effect, likely due to the closure of several PRCs from which data were collected, as well as lockdown measures that restricted the operation of markets and events—key sources of substantial solid waste generation. These factors reduced the amount of solid waste generated in urban settings, thereby limiting the materials that waste pickers could recover. Consequently, the estimated CO_2 emissions avoidance from diverting waste from disposal sites declined over time. Despite this reduction, the overall trend remained relatively stable (see Fig. 4), with occasional increases attributed to CO_2 emissions avoidance from aluminium recovery (see Fig. 6). Indeed, as demonstrated by Friedrich and Trois (2013), aluminum has a higher GHG emission factor compared to other recyclable materials, leading to significant CO_2 emissions savings when integrated into the recycling chain.

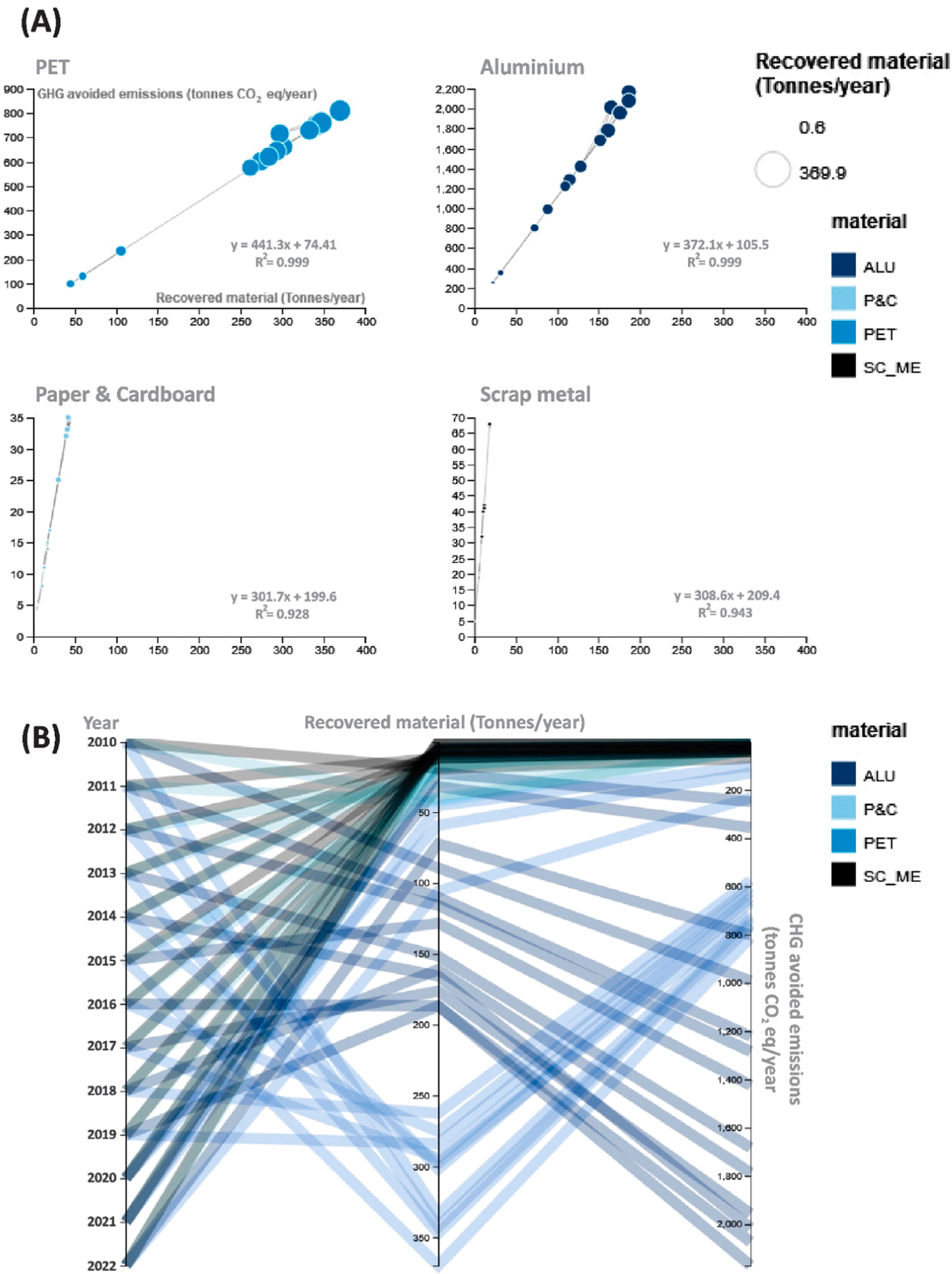

Fig. 7. Correlation between the estimates of GHG emissions avoidance and quantities of recovered materials (i.e., solid waste) from waste picker activities over the years (Panel A). Relationship between years, quantities of recovered materials, and estimates of GHG emissions avoidance (Panel B). ALU = Aluminium, P&C = Paper & Cardboard, and SC-ME = Scrap metal.

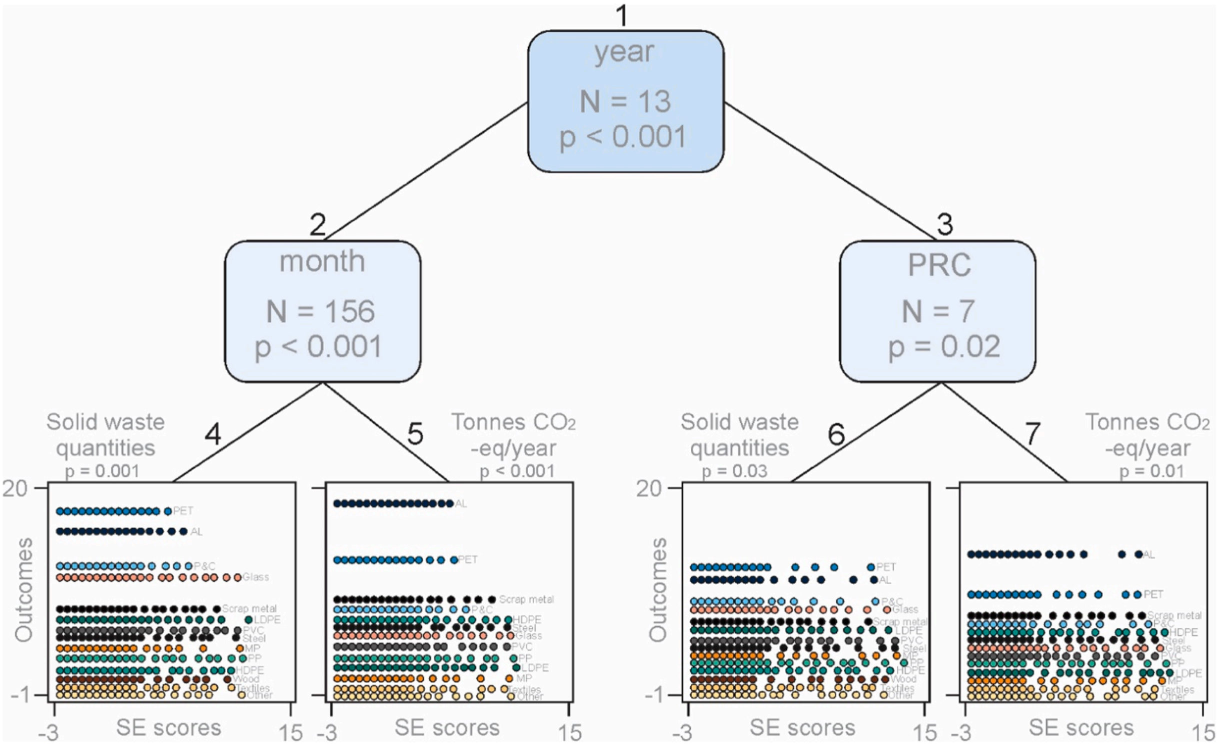

Fig. 8. The estimate mixed-effects tree model for the probability of solid waste quantities and GHG avoided emissions. Panes depict subgroup sizes (N) and outcomes based on p-values. The terminal nodes represent the overall outcomes with standard errors (SE) for each waste type based on their quantities and estimates of GHG avoided emissions.

4.2. Putting informal waste pickers in radar of MSWM and GHG mitigation

Recognizing the role of individuals who derive their livelihood from resource recovery and waste recycling, as highlighted by Buch et al. (2021) as well as Dean and Asen (2024), underscores their significance as key stakeholders within MSWM systems. Despite this, local governments often overlook these insights when setting up new waste management programs or establishing recycling centers (Gutberlet and Carenzo, 2020). Consequently, there appears to be a persistent lack of recognition that waste pickers also play a significant role in mitigating climate change by diverting recyclables from landfills. Most waste pickers supplying the PRCs assessed in our study belong to socially marginalized groups, often including individuals experiencing homelessness. It is crucial to first reduce their extreme vulnerability through targeted social policies and then actively include these individuals in discussions and consultations regarding municipal waste management plans. They must not be marginalized or disadvantaged within integrated waste management systems, as emphasized by Gonzenbach and Coad (2007). Additionally, gaining more traction in circular economy perspectives – beyond issues purely related to MSWM – requires empowering waste pickers by establishing collaborative networks of stakeholders (e.g., recycling centers, industries, and governmental agencies) and providing access to technologies and markets that enable waste pikers to manufacture upcycled products (Buch et al., 2021). By addressing their social and economic challenges, these workers can be more effectively integrated into formal MSWM systems. In the context of Salvador city, waste pickers have long endured a lack of labor rights, extensive work hours, and significant health risks due to unsanitary working conditions (Gama and Silva, 2018). However, while the aspiration for inclusive waste management practices may seem idealistic, particularly given Brazil's persistent inequalities that disproportionately affect the poorest segments of society (Lobato, 2016; Souza et al., 2021), it remains crucial to advocate for improved working conditions and support for these waste workers.

The economic feasibility of waste collection, considering its social and environmental advantages has been substantiated (Gomes and Coutinho-Nóbrega, 2005). However, informal waste pickers experience fewer direct and indirect benefits, primarily due to their precarious working conditions and limited social acceptability. Sellers of recycled materials, recycling industries, and municipally managed landfills often reap the highest profits and business opportunities, such as energy generation from biogas production (Lino and Ismail, 2011). Recognizing informal waste pickers as integral participants in this valuable waste management chain and acknowledging the resultant GHG mitigation benefits is a topic warranting discussion. Consequently, it is essential to explore ways to achieve tangible and feasible social justice within this framework. Waste pickers in many Latin American cities have made significant progress by forming cooperatives, associations, and regional networks, as well as participating in social movements (see Colombijn and Morbidini, 2017; Dutra et al., 2018). While these efforts have fostered dialogue with governmental bodies and partnerships with recycling industries, informal waste pickers, such as those assessed in this study, urgently need improvements to their livelihoods to fully benefit from such initiatives. By enhancing the conditions of informal waste pickers, they can truly become integrated into the circular economy with regards to the recycling process. Moreover, they can be formally recognized as urban recycling workers, thereby enhancing their potential to recover solid waste and contribute to GHG mitigation efforts.

Finally, out of the 5570 Brazilian municipalities, 51 % still rely on dumps for waste disposal, including recyclable materials (ABRELPE, 2022), thereby contributing to uncontrolled GHG emissions. Although comprehensive data on waste pickers across all Brazilian territories is lacking, estimates suggest there could be up to 800,000 workers in this informal sector (Dagnino and Johansen, 2017). Some municipal governments in Brazil have created employment classifications to monitor the waste picker population and assess the economic impacts they generate (Buch et al., 2021). Nevertheless, this effort remains in its infancy from a national perspective, with limited understanding of the environmental benefits stemming from their waste recovery activities. By diverting recyclables away from dumps, these informal workers contribute significantly to mitigating climate change, highlighting the need for greater recognition and integration in the MSWM debates and climate change agendas.

5. Conclusions

Our study demonstrates the substantial contribution of informal waste pickers to the recovery of recyclables in a large urban setting, with results in some cases comparable to those achieved by formal workers, such as waste cooperatives. This was evidenced through a temporal series analysis, which highlights the consistent role of informal waste pickers in MSWM. Furthermore, the findings underscore the critical importance of waste pickers in reducing GHG emissions and advancing circular economy practices in Brazil. While many studies have particularly shown the pivotal role of informal waste pickers in addressing the solid waste pollution crisis, our long-term research offers new insights into the temporal dynamics of the recovery of recyclable materials and reinforces the need to prioritize attention and support for this sector. Integrating waste pickers into formal waste management systems and providing them with necessary support and resources could enhance their efficiency and impact. Recognizing and formalizing the contributions of this marginalized workforce is essential for developing sustainable and inclusive waste management policies. Such efforts could substantially reduce CO_2 emissions, alleviate urban poverty, and contribute to global climate change mitigation.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or non-for-profit sectors.

CRediT authorship contribution statement

Reis-Filho José Amorim: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giarrizzo Tommaso:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Gutberlet Jutta:** Writing – review & editing, Writing – original draft, Visualization, Validation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors did not use any generative AI in scientific writing or in any step of the research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are deeply grateful to the managers and owners of the pre-recycling centers involved in this study for voluntarily providing the necessary data for this survey. We also extend our sincere thanks to the *Guerreiros da Paz* NGO for allowing J.A. Reis-Filho to accompany their weekly operations on the streets of Salvador, providing valuable insights into the challenging realities faced by waste pickers. JAR-F received financial support post-doctoral fellowship from FADESP (#339020/2022). TG is funded by the Brazilian National Council for Scientific and Technological Development, CNPq (#308528/2022-0).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.clwas.2025.100217.

Data availability

The raw data are provided in the Supplementary Material and additional information or specific datasets can be obtained by contacting the corresponding author.

References

ABRELPE. (2022). Panorama dos Resíduos Sólidos no Brasil 2022. Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais (ABRELPE). ⟨https://www.abrema.org.br/⟩.

Araújo, S.S.L., 2015. Gravimetria dos resíduos sólidos do município de Salvador – BA. Trabalho de conclusão de curso. : Gravim. De. Resíduos. Virapuru Train. Cent. 78.

Arora K. (2022) Global plastics treaty: Waste pickers ready to talk, WIEGO. ⟨https://www.wiego.org/blog/global-plastics-treaty-waste-pickers-ready-talk⟩ (Accessed 23 December 2024).

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed effects models using lme4. J. Stat. Softw. 67, 1–48. https://doi.org/10.18637/jss.v067.i01.

Barford, A., Ahmad, S.R., 2021. A call for a socially restorative circular economy: waste pickers in the recycled plastics supply chain. Circ. Econ. Sustain. 1, 761–782. https://doi.org/10.1007/s43615-021-00056-7.

Barr, D.J., Levy, R., Scheepers, C., Tily, H.J., 2013. Random effects structure for confirmatory hypothesis testing: keep it maximal. J. Mem. Lang. 68, 255–278. https://doi.org/10.1016/j.jml.2012.11.001.

Beltran-Siñani, M., Gil, A., 2021. Accounting greenhouse gas emissions from municipal solid waste treatment by composting: a case of study Bolivia. Eng 2, 267–277. https://doi.org/10.3390/eng2030017.

Bogner, J., Abdelrafie Ahmed, M., Diaz, C., Faaij, A., Gao, Q., Hashimoto, S., Zhang, T., 2007. Waste management, Chapter 10. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation of Climate Change. Cambridge University Press.

Brooks, A.L., Wang, S., Jambeck, J.R., 2018. The Chinese import ban and its impact on global plastic waste trade. Sci. Adv. 4 (6), eaat0131. ⟨https://doi.org/10.1126/sciadv.aat0131⟩.

Buch, R., Marseille, A., Williams, M., Aggarwal, R., Sharma, A., 2021. From waste pickers to producers: an inclusive circular economy solution through development of cooperatives in waste management. Sustainability 13 (6), 8925. https://doi.org/10.3390/su13168925.

Caldas, A.H.M., 2007. Análise da disposição de resíduos sólidos e da percepção dos usuários em áreas costeiras –um potencial de degradação ambiental. Monografia. Universidade Federal da Bahia, Salvador, BA, Brasil.

Chabuk, A., Al-Ansari, N., Hussain, H.M., Knutsson, S., Pusch, R., 2015. Present status of solid waste management at Babylon Governorate, Iraq. Engineering 7, 408–423. https://doi.org/10.4236/eng.2015.77037.

Chen, T.-C., Lin, C.-F., 2008. Greenhouse gases emissions from waste management practices using life cycle inventory model. J. Hazard. Mater. 155, 23–31.

Chokhandre, P., Singh, S., Kashyap, G.C., 2017. Prevalence, predictors and economic burden of morbidities among waste-pickers of Mumbai, India: a cross-sectional study. J. Occup. Med. Toxic. 12, 30. https://doi.org/10.1186/s12995-017-0176-3.

Conceição, M.M. (2005). Os empresários do lixo: um paradoxo da modernidade, second ed., Átomo, Campinas.

Colombijn, F., Morbidini, M., 2017. Pros and cons of the formation of waste-pickers' cooperatives: a comparison between Brazil and Indonesia. Decision 44, 91. https://doi.org/10.1007/s40622-017-0149-5.

Cook, E., Velis, C.A. (2020). Global Review on Safer End of Engineered Life, 34–36.

Dagnino, R.S., Johansen, I.C., 2017. Os catadores no Brasil: características demográficas e socioeconômicas dos coletores de material reciclável, classificadores de resíduos e varredores a partir do censo demográfico de 2010. Merc. De. Trab. 62, 115–125.

Damgaard, A., Larsen, A.W., Christensen, T.H., 2009. Recycling of metals: accounting of greenhouse gases and global warming contributions. Waste Manag. Res. 27, 773–780.

Dean, M.R.U., Asen, M.C., 2024. The contribution of global waste picker organizations in responding to the plastic pollution crisis. Camb. Prism. Plast. 2 (e29), 1–9. https://doi.org/10.1017/plc.2024.24.

Dias, S.M., 2016. Waste pickers and cities. Environmental & Urbanization. International Institute for Environment and Development (IIED, pp. 1–16. doi:10.1177/0956247816657302.

Dutra, R.M., Yamane, S., Siman, L.H., 2018. Influence of the expansion of the selective collection in the sorting infrastructure of waste pickers' organizations: a case study of 16 Brazilian cities. Waste Manag. 77, 50–58. https://doi.org/10.1016/j.wasman.2018.05.009.

Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (2006). IPCC Guidelines for National Greenhouse Gas Inventories, 5, Waste. IGES.

EIU - The Economist Intelligence Unit. (2017). Avances y desafíos para el reciclaje inclusivo: evaluación de 12 ciudades de América Latina y el Caribe. New York,NY: EIU United Nations Human Settlements Programme (UN-HABITAT) and Norwegian Institute for Water Research (NIVA) (2022) Leaving no one behind: How a global instrument to end plastic pollution can enable a just transition for the people informally collecting and recovering waste. ⟨https://unhabitat.org/sites/default/files/2022/11/un-habitat_niva_report_leaving_no_one_behind.pdf⟩.

Friedrich, E., Trois, C., 2013. CHG emission factors developed for the recycling and composting of municipal waste in South African municipalities. Waste Manag. 33, 2520–2531.

Gama, S.H., Silva, S.C., 2018. The Chain of casualization: a case study of recyclers from Salvador, Bahia. Argumentum 10 (3), 302–316. https://doi.org/10.18315/argumentum.v10i3.18784.

Gautam, M., Agrawal, M., 2021. Greenhouse gas emissions from municipal solid waste management: a review of global scenario. Carbon Footprint Case Studies: Municipal Solid Waste Management, Sustainable Road Transport and Carbon Sequestration. Springer, Singapore, pp. 123–160.

Gelman, A., Hill, J., 2007. Data Analysis Using Regression and Multilevel/Hierarchical Models. Cambridge University Press, Cambridge.

Gichamo, T., Gökçekus, H., 2019. Interrelation between climate change and solid waste. J. Environ. Pollut. Control 2, 104.

Guabiroba, R.C.S., Jacobi, P.R., Abegão, L.H., Besen, G.R., 2023. Sustainability performance evaluation of municipal selective collection systems applied to a case study. Braz. J. Environ. Sci. 58 (1), 1–10. https://doi.org/10.5327/Z2176-94781482.

Gomes, H.P., Coutinho-Nóbrega, C., 2005. Economic viability study of a separate household waste collection in a developing country. Waste Manag. 7, 116–123.

Gonzenbach, B., Coad, A. (2007). Solid waste management and the millennium development goals: links that inspire action. In: CWG Publication Series No. 3 (Ed.), Collaborative Working Group on Solid Waste Management in Low- and Middle-Income Countries.

Gutberlet, J., 2023. Global plastic pollution and informal waste pickers. Camb. Prism. Plast. 1 (e9), 1–16. https://doi.org/10.1017/plc.2023.10.

Gutberlet, J., Besen, G.R., Morais, L.P., 2020. Participatory solid waste governance and the role of social and solidarity economy: experiences from São Paulo, Brazil. Detritus 13, 167–180.

Gutberlet, J., Carenzo, S., Kain, J.-H., de Azevedo, A.M.M., 2017. Waste picker organizations and their contribution to the circular economy: two case studies from a global South perspective. Resources 6 (52), 1–12.

Gutberlet, J., Carenzo, S., 2020. Waste pickers at the heart of the circular economy: a perspective of inclusive recycling from the global South. Worldw. Waste. J. Interdiscip. Stud. 6, 1–14. https://doi.org/10.5334/wwwj.50.

Gutberlet, J., Danoso, M., 2015. Zero waste: climate mitigation and poverty reduction with cooperative recycling. In: Hirsch, T., Lottje, C., Netzer, N. (Eds.), Exploring Sustainable Low Carbon Development Pathways. Pioneers of Change. 21 Good Practices for Sustainable Low Carbon Development in Developing Countries. Friedrich-Ebert-Stiftung, Berlin, pp. 25–37. ⟨https://library.fes.de/pdf-files/iez/11664.pdf⟩.

Hamed, K.H., Ramachandra Rao, A., 1998. A modified Mann-Kendall trend test for autocorrelated data. J. Hydrol. 204, 182–196. https://doi.org/10.1016/S0022-1694(97)00125-X.

Hartmann, C.D., 2012. Uneven urban spaces: accessing trash in Managua, Nicaragua. J. Lat. Am. Geogr. 11 (1), 143–163. https://doi.org/10.1353/lag.2012.0003.

Hastie, T., Tibshirani, R., Friedman, J., 2009. The Elements of Statistical Learning. Springer, New York, NY.

Instituto Brasileiro de Geografia e EstatísticaIBGE). (2023). Estimativas de População para os Municípios Brasileiros: Revisão 2022, IBGE, Rio de Janeiro. ⟨https://www.ibge.gov.br/estatisticas/sociais/populacao/9103-estimativas-de-populacao.html?=&t=o-que-e⟩ (Accessed 14 March 2024).

IPCC). (2006). IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Institute for Global Environmental Strategies, IGES. Japan.

IPCC, 2008. In: Eggleston, H.S., Miwa, K., Srivastava, N., Tanabe, K. (Eds.), IPCC guidelines for national greenhouse gas inventories - a primer. Prepared by the National Greenhouse Gas Inventories Programme, 2008. IGES, Japan, pp. 1–20.

International Labour Organization, WIEGO. (2013). Women and men in the informal economy: a statistical picture second ed., International Labour Organization, Geneva. ⟨www.ilo.org/wcmsp5/groups/public/—dgreports/—stat/documents/publication/wcms_234413.pdf⟩).

Kain, J.-H., Zapata, P., Mantovani, A.A.M., Carenzo, S., Charles, G., Gutberlet, J., 2022. Characteristics, challenges and innovations of waste picker organizations: a comparative perspective between Latin American and East African countries. PLoS ONE 17 (7), e0265889. https://doi.org/10.1371/journal.pone.0265889.

Kasinja, C., Tilley, E., 2018. Formalization of informal wastepickers' cooperatives in Blantyre, Malawi: a feasibility assessment. Sustainability 10 (4), 1149. https://doi.org/10.3390/su10041149.

Kariuki, J.M., Bates, M., Magana, A., 2019. Characteristics of waste pickers in Nakuru and Thika municipal dumpsites in Kenya. Curr. J. Appl. Sci. Technol. 37 (1), 1–11. https://doi.org/10.9734/cjast/2019/v37i130272.

King, M., Gutberlet, J., 2013. Contribution of cooperative sector recycling to greenhouse gas emissions reduction: a case study of Ribeirão Pires, Brazil. Waste Manag. 33, 2771–2780.

King, M.F., Gutberlet, J., da Silva, D.M., 2016. Contribuição de cooperativas de reciclagem para a redução de emissão de gases de efeito estufa (contribution of recycling cooperatives to the reduction of greenhouse gas emissions). In: Jaquetto Pereira, B.C., Lira Goes, F. (Eds.), Catadores de Materiais recicláveis: Um Encontro Nacional. Instituto de Pesquisa Econômica Aplicada IPEA, Brasília, pp. 507–536.

Kumar, A., Samadder, S.R., Kumar, N., Singh, C., 2018. Estimation of the generation rate of different types of plastic wastes and possible revenue recovery from informal recycling. Waste Manag. 79, 781–790. https://doi.org/10.1016/j.wasman.2018.08.045.

Lee, W., Grimm, K.J., 2018. Generalized linear mixed-effects modeling programs in R for binary outcomes. Struct. Equ. Model. A Multidiscip. J. 25, 824–828. https://doi.org/10.1080/10705511.2018.1500141.

Lino, F.A.M., Ismail, K.A.R., 2011. Energy and environmental potential of solid waste in Brazil. Energy Policy 39, 3496–3502. https://doi.org/10.1016/j.enpol.2011.03.048.

Lobato, L.V.C., 2016. Social policies and social welfare models: fragilities of the Brazilian case. Essay 40, 87–96. https://doi.org/10.1590/0103-11042016S08.

Marchi, C.M.D.F., Santana, J.S., 2022. Waste pickers of recyclable materials: analysis of the socioeconomic profile in the city of Salvador, Bahia, Brazil. Inter. ções 23 (2), 413–422. https://doi.org/10.20435/inter.v23i2.3058.

Medina, M., 2008. The Informal recycling Sector in Developing Countries: Organizing Waste Pickers to Enhance their Impact. Gridlines; No. 44. © World Bank, Washington, DC. ⟨http://hdl.handle.net/10986/10586⟩.

Mesquita, J.L.C., Gutberlet, J., de Araujo, K.P., Cruvinel, V.R.N., Duarte, F.H., 2023. Greenhouse gas emission reduction based on social recycling: a case study with waste picker cooperatives in Brasília, Brazil. Sustainability 15, 9185. https://doi.org/10.3390/su15129185.

Meteoblue. (2024). Weather close to you. Swiss. ⟨https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/salvador_brazil_3450554⟩.

Mitlin, D., 2008. With and beyond the state—co-production as a route to political influence, power and transformation for grassroots organizations. Environ. Urban. 20 (2), 339–360.

Morais, J., Corder, G., Golev, A., Lawson, L., Ali, S. (2022). Global review of human waste-picking and its contribution to poverty alleviation and a circular economy. Environ. Res. https://doi.org/1088/1748-9326/ac6b49.

Oliveira, M.C.V., Klafke, R., Chaerki, S.F., 2022. The challenge of urban solid waste management in Brazil. Econ. Soc. Y. Territ. 68, 177–206. https://doi.org/10.22136/est20221738.

Paul, J.G., Arce-jaque, J., Ravena, N., Villamor, S., 2012. Integration of the informal sector into municipal solid waste management in the Philippines – What does it need? Waste Manag. 32 (11), 2018–2028.

Pereira, G.C., Fernandes, C.M., 2022. Reforma urbana e direito à cidade. Salvador. Observatório das Metrópoles. first ed., Letra Capital, Rio de Janeiro 280.

Pimenteira, C.A.P., Pereira, A.S., Oliveira, L.B., Rosa, L.P., Reis, M.M., Henriques, R.M., 2004. Energy conservation and CO_2 emission reductions due to recycling in Brazil. Waste Manag. 24, 889–897.

Pitoyo, A.J., Aditya, B., Amri, I. (2020). The impacts of COVID-19 pandemic to informal economic sector in Indonesia: theoretical and empirical comparison. E3S Web of Conf. https://doi.org/10.1051/e3sconf/202020003014.

R Core Team. (2022). R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ⟨https://www.R-project.org/⟩.

Samson, M. (2010). Reclaiming Reusable and Recyclable Materials in Africa a Critical Review of English Language Literature, Women in Informal Employment: Globalizing and Organizing (WIEGO)), Cambridge, MA. ⟨www.wiego.org/sites/default/files/publications/files/Samson_WIEGO_WP16.pdf⟩).

Santos, H.S., Oliveira, A.L.C., Freitas, W., 2023. Diagnóstico Socioambiental e análise gravimétrica de resíduos sólidos em três praias urbanas da cidade de Salvador (Bahia). Rev. Bras. De. Meio Ambient. 11 (1), 227–247.

Sembiring, R., Nitivattananon, V., 2010. Sustainable solid waste management toward an inclusive society: integration of the informal sector. Resour. Conserv. Recycl. 54 (11), 802–809.

SECIS, 2019. Secretaria de Sustentabilidade, Inovação e Resiliência. Salvador Resiliente. Prefeitura De. Salvador 227.

Singh, C.K., Kumar, A., Roy, S.S., 2018. Quantitative analysis of the methane gas emissions from municipal solid waste in India. Sci. Rep. 8, 2913. https://doi.org/10.1038/s41598-018-21326-9.

da Silva, P.F., Besen, G.R., Ribeiro, H., 2022. Payment for environmental services for waste pickers: systematic literature mapping. Energy Environ. Resour. 11 (2), 1–54.

SNIS - National Sanitation Information System. (2021). Diagnósticos SNIS 2020 – Planilhas em Microsoft Excel. Secretaria Nacional de Saneamento, Governo do Brasil (Accessed 21 March 2024) at: ⟨http://antigo.snis.gov.br/diagnosticos⟩.

Souza, H.G., Tabosa, F.J.S., Araújo, J.A., Castelar, P.U.C., 2021. A spatial analysis of how growth and inequality affect poverty in Brazil. Braz. J. Public Adm. 55 (2), 459–482. https://doi.org/10.1590/0034-761220190349.

Taghipour, H., Amjad, Z., Aslani, H., 2016. Characterizing and quantifying solid waste of rural communities. J. Mater. Cycles Waste Manag. 18, 790–797. https://doi.org/10.1007/s10163-015-0365-z.

Tucker, J.L., Anantharaman, M., 2020. Informal work and sustainable cities: from formalization to reparation. One Earth 3, 290–299.

Tun, M.M., Juchelková, D., 2019. Estimation of greenhouse gas emissions: an alternative approach to waste management for reducing the environmental impacts in Myanmar. Environ. Eng. Res. 24, 618–629.

UNEP. (2013). Thematic Focus: Ecosystem Management, Environmental Governance, Harmful Substances and Hazardous Waste: Municipal Solid Waste: is it Garbage or Gold? ⟨https://na.unep.net/geas/archive/pdfs/GEAS_Oct2013_Waste.pdf⟩).

Vieira, M.E.A. (2011). Percepção de autonomia entre catadores de materiais recicláveis de associações e organizações privadas de Fortaleza. ⟨http://www.abrapso.org.br/siteprincipal/images/Anais_XVENABRAPSO/138.pdf⟩.

Voukkali, I., Papamichael, O., Loizia, P., Zorpas, A.A., 2024. Urbanization and solid waste production: prospects and challenges. Environ. Sci. Pollut. Res. 31, 17678–17689.
WIEGO. (2021a). Waste Pickers: Essential Service Providers at Risk. ⟨www.wiego.org/waste-pickers-essential-service-providers-risk⟩).
WIEGO, 2021b. Reducing greenhouse gas emissions through inclusive recycling. Resources & AdvisorGroup 28. ⟨https://www.wiego.org/ghg⟩.
Wilson, D.C., Costas, V., Cheeseman, C., 2006. Role of informal sector recycling in waste management in developing countries. Habitat Int. 30 (4), 797–808.
Yousafzai, M.T., Nawaz, M., Xin, C., Tsai, S.B., Lee, C.,H., 2020. Sustainability of waste picker sustain opreneurs in Pakistan's informal solid waste management system for cleaner production. J. Clean. Prod. 267, 121913.
Zeileis, A., Fokkema, M. (2019). glmertree: Generalized Linear Mixed Model Trees (Version R Package Version 0.2-0). ⟨https://cran.r-project.org/package=glmertree⟩.
Zhang, Z., Chen, Z., Zhang, J., Liu, Y., Chen, L., Yang, M., Osman, A.I., Farghali, M., Liu, E., Hassan, D., Ihara, I., Lu, K., Rooney, D.W., Yap, P., 2024. Municipal solid waste management challenges in developing regions: a comprehensive review and future perspectives for Asia and Africa. Sci. Total Environ. 930, 172794. https://doi.org/10.1016/j.scitotenv.2024.172794.
Zhu-Barker, X., Bailey, S.K., Paw, U.K.T., Burger, M., Horwath, W.R., 2017. Greenhouse gas emissions from green waste composting windrow. Waste Manag. 59, 70–79.

Further reading

IPCC, 2018. Intergovernmental Panel on Climate Change. Global Warming of 1.5 ∘C. https://www.ipcc.ch (Accessed 20 March 2024).
IPCC, 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. ⟨https://www.ipcc.ch/report/ar6/wg2/⟩ (Accessed 20 March 2024).