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Greenhouse Gas Emission Reduction Based on Social Recycling: A Case Study with Waste Picker Cooperatives in Brasília, Brazil

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Abstract: Solid waste is a major contributor to climate change due to the release of greenhouse gases (GHGs) during the decomposition of waste. As a consequence, waste should be avoided, and an appropriate destination should be given to all materials that are discarded. While not the only strategy, recycling is a fundamental process in addressing this problem. In 2013, a study carried out with one waste picker cooperative in São Paulo has paved the way to assessing the impact of recycling on GHG emission reduction, by using the methodological tools of the Clean Development Mechanism of the United Nations Convention on Climate Change. The objective of our study is to evaluate the applicability of this methodology to different work environments, measuring greenhouse gas emission reductions and energy saving as a consequence of recycling. Our study involves three waste picker organizations located in the city of Brasília, Brazil. The three cooperatives have made secondary data for 2019 on their material input and output available. The following variables were considered: type and amount of solid waste collected, type of machines used, energy sources and transport routes. The data analysis verified that waste picker organizations significantly contribute to the reduction of greenhouse gas emissions and energy savings. We conclude that this methodology can be applied successfully to calculate emission reductions and energy savings from material recycling in different recycling contexts. Ultimately, this research recognizes the positive environmental and climate impact of the work of waste pickers, which needs to be recognized and remunerated.

Keywords: greenhouse gas emissions (GHG); clean development mechanism (CDM); recycling; carbon credits; waste pickers

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1. Introduction

The greenhouse gas (GHG) effect is a natural phenomenon essential for the existence of life on Earth. However, human activities have aggravated this phenomenon, causing numerous environmental problems. Emissions of greenhouse gases into the atmosphere cause climate change across the planet, threatening the long-term survival of humans and other species. Tackling this global problem is urgent and requires collective collaboration. In 1992, the United Nations Convention on Climate Change was signed in New York, where the countries gathered and considered the climate change scenario and the type of industrial development in each country in order to create collective responsibilities for the reduction of GHGs and obligations regarding public policies to mitigate climate change. In 1997, the Kyoto Protocol was created to reinforce these responsibilities, which was succeeded by the Paris Agreement in 2015 during the 21st Conference of the Parties (COP21) of the United Nations Convention on Climate Change. According to special reports of the Intergovernmental Panel on Climate Change, human activities have caused 1 °C of global warming in the last 30 years [1] and 1.9 °C specifically from 2011 to 2020 [2]. Between the years 2010 to 2020, it is estimated that a net total of 40 to 50 billion tons of CO_2 have been emitted per year [1]. Considering different scenarios, there is a greater than 50% likelihood that global warming will reach or exceed 1.5 °C between 2021 and 2040, even considering a very low greenhouse gas emissions scenario [2].

The waste decomposition process releases greenhouse gases, also commonly expressed in the related literature as CO_2 equivalents (CO_2-eq.) of gases responsible for changing our climate [3]). The main climate-relevant GHG generated through solid waste management activities are methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) [4,5]. The greenhouse effect and climate change related to it also have an indirect but intense negative impact on public health due to ecosystem changes that, in turn, can modify the length of the seasons, for example, provoke longer winters, impact the increase or decrease of some vectors and, consequently, increase the incidence of infectious diseases and noncommunicable diseases [6].

In 2018, a total of 79 million tons of urban waste were generated in Brazil. Of this amount, 40.5% was dumped in inappropriate places by 3001 municipalities. That is, 29.5 million tons of urban solid waste ended up going to dumps or controlled landfills, which do not have the necessary systems and measures in place to protect public health and the environment [7–9].

In Brasília, the capital of Brazil, located in the Federal District (DF), only 300 tons (12%) of urban waste are recycled, and this activity is carried out by waste pickers, who work either independently or organized in cooperatives or associations, as in many other parts of the country and also in other parts of the world). For almost 60 years, Brasília hosted the largest dump in Latin America, covering an area of 201 ha, equivalent to 280 football fields, which received 40 million tons of waste during the period of its existence [10] Fortunately, with the construction of a new landfill, in 2017, the dump was officially closed one year later [11].

The closure of the dump meant a significant change not only for the city's administration but mostly for the independent waste pickers whose access to the dump was now denied. This represents the majority of all waste pickers working in Brasília, where only 10% are organized [12]. The DF Urban Cleaning Services (SLU), was aware of the changes in the life of the waste pickers after the closure of the dump and signed 28 contracts with waste picker organizations (WPOs), 11 for selective waste collection and 17 for sorting recyclable materials. For that purpose, new waste picker organizations were created as recycling centers at warehouses provided by the SLU [13]. The current selective waste collection program of Brasília for households and businesses targets all recyclable materials (paper, plastic, metal and glass) without any common waste and organic materials mixed in. The city reiterates that separate collection begins with the correct separation by the consumers at the household level and by the businesses at the industry level [13]. It is then transported to the cooperatives to be properly separated and sold to the recycling industry.

In Brazil, about 30% of the waste pickers are organized. The organization of waste pickers began with the 1st National Congress of Waste Pickers in 2001 [14], which led to the formation of cooperatives and associations, based on principles of solidarity and ecological economy [15]. These emerging waste picker organizations were striving for social inclusion and were driven by the National Solid Waste Policy [16]. According to Silva [16] cooperatives are seen as a solution adopted in order to add value to the product and to increase the income of waste pickers. The federal government also created some tools to further stimulate the growth and strengthening of waste picker cooperatives, specifically Decree No. 7405/2010, which instituted the Pró Catador program and the project Cataforte II Solidarity Logistics (The decree was revoked in 2020. A working group under the new government in 2023 has prepared a proposal for its re-establishment (Ordinance Number 2 of 5 January 2023) [17].

The solidarity economy and the circular economy are part of sustainability strategies and have been an increasingly frequent agenda in the elaboration of public policies that seek to protect natural resources and reduce environmental degradation and pollution [18]. Instead of linear material flows, the circular economy proposes cradle-to-cradle as a fundamental principle, which allows products and materials after being discarded as waste to potentially be reinserted into the production process [19]. Waste picker cooperatives are key actors in the recycling process and contribute to circularity, while also playing a role in supporting livelihoods and improving working conditions [20].

Part of this new economic perspective is put into practice through 'reverse logistics', which is a concept similar to the circular economy and also includes the consolidation and transport of recyclables and their reintroduction into the product chain [21,22]. According to the Brazilian National Solid Waste Policy, reverse logistics works as an instrument of economic and social development that enables the collection and return of materials to the business sector, for reuse, refurbishing or recycling [23].

Over the past fifty years, the production of materials that do not decompose easily and that are toxic to the environment has increased significantly, with plastics being particularly problematic. In 2019, 348 million tons of plastic materials were produced worldwide [24]. Waste pickers play a pivotal role in recovering these materials for recycling [25].

In most Global South countries, providing recycling services to all citizens remains an enormous challenge, and the current lack of waste collection and recycling significantly threatens local public health and overall ecological integrity in these parts of the world [20]. In most cities in Brazil, selective waste collection only covers a small part of the city, and not all households where there is selective waste collection contribute to it [26].

Despite the obvious link between the work of waste pickers diverting materials for recycling and the benefits to the climate from this activity, there are very few studies that explicitly make that connection. A first investigation carried out in 2013, in São Paulo, Brazil, focused on measuring the climate contributions from recycling [3]. This research developed a calculator to quantity GHG emissions avoided and energy saved through the work of this waste picker organization (WPO). The objective of the current study is to evaluate the applicability of this methodology to other geographic contexts. The organization, availability of infrastructure and machinery as well as the expenses related to energy and water consumption and transportation to and from the WPO vary significantly between each WPO. To further refine the methodology, allowing its use by any other WPO, the authors choose two recycling cooperatives in Brasília as their case study sites to quantify their GHG emission reduction.

The aim of this research is to help understand the environmental and climate benefits of the work of waste pickers to reward their service. The research generates information that can help raise the awareness of actors in waste management for the investment in reverse logistic schemes, the circular economy and social and solidarity economy, prioritizing environmental and climate protection through selective waste collection and recycling [27–29].

The next section will briefly describe our methodology. We will highlight the specific context of the cooperatives in Brasília that are part of this case study and will explain the procedure used for the data collection and analysis. We then present the results and follow with a discussion of our findings. In this section, we highlight how waste pickers act as agents for GHG emission reduction and how they contribute to the environment. The discussion also shows some of the remaining challenges as well as the need for waste pickers to become rewarded through the certification for GHG emission reductions. Finally, in the conclusion, we summarize the key points of our research and provoke reflections on the certification of waste pickers for their environmental service.

2. Methodology

The following section introduces the case study contexts and explains the data used in our analysis, which was adapted from the existing method [30], which was designed to calculate greenhouse gas emission reductions and energy savings. We collected secondary data related to the annual material inventory for each cooperative (2019 data), informal conversations were conducted with some of the leaders in the three WPOs, to confirm specific facts and to complement socio-demographic information on the three WPOs.

2.1. Location of the Study Sites

This analytical, cross-sectional case study involves three waste picker organizations located in the most populous area of the Federal District (Figure 1). The first WPO is called *Recicle a Vida* (A) and is located in the administrative region of Samambaia (193,485 inhabitants), in the Federal District (DF). The other two WPOs are waste recovery facilities operated by the city administration (SLU); they are called *Plasferro* (B) and *Coopere* (C). Both are located in the most populated administrative region, which is called Ceilândia (398,374 inhabitants). The following figure provides a view inside the three different workspaces *Recicle a Vida* (Figure 2A), *Plasferro* (Figure 2B) and *Coopere* (Figure 2C).

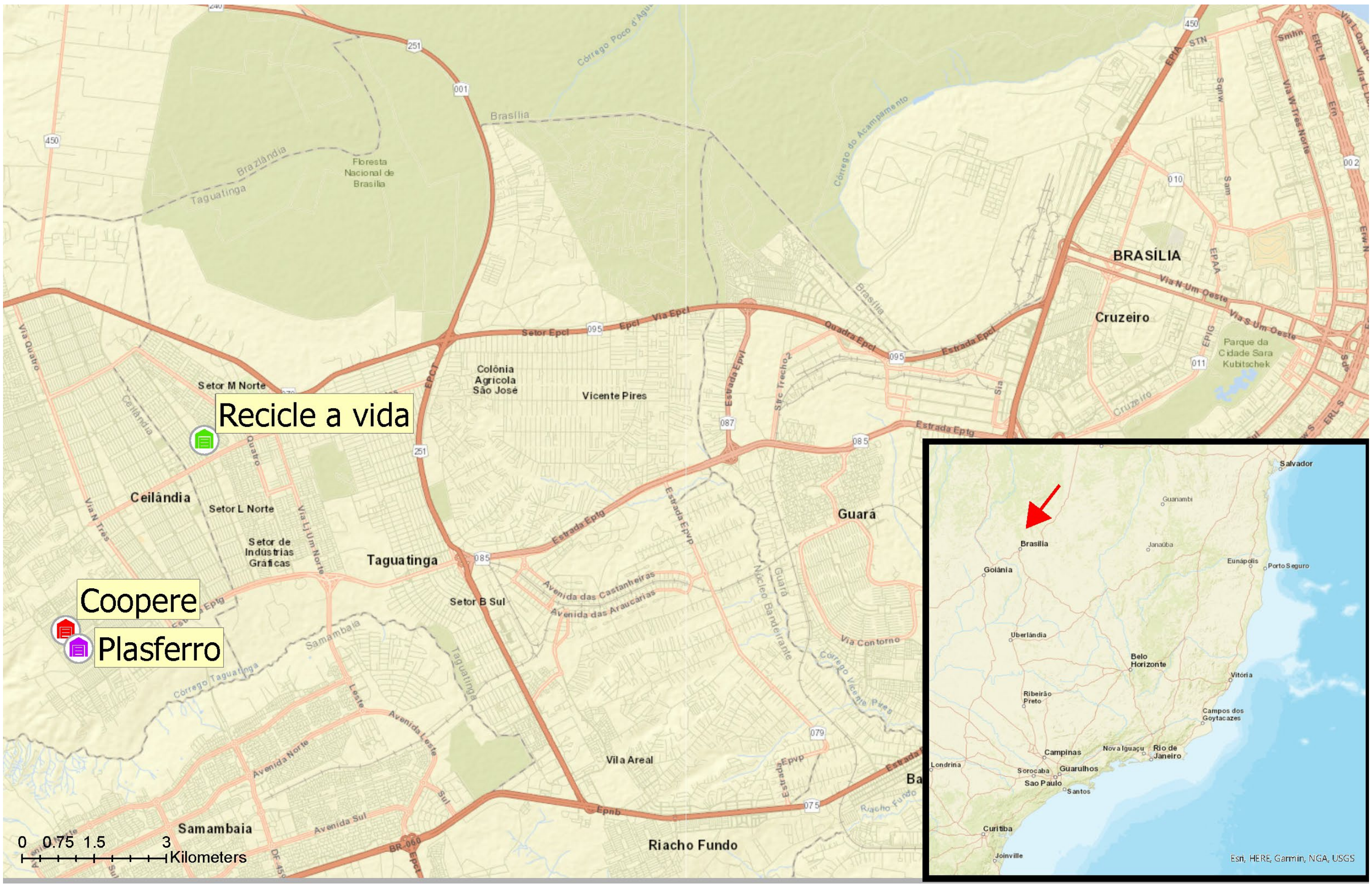

Figure 1. Localization map of the three WPOs in the Federal District (DF).

A significant proportion of the local population in these areas (40% in Ceilândia and 38% in Samambaia) was born in other states and has a migrant background. They came to the capital to accompany family members or in search of work. Furthermore, 96% of the population declares that they know how to read and write and 38% have completed high school. In Ceilândia, 22.4% of the population and in Samambaia 17.5% of the residents work on their own account, mostly in the informal sector. On average, the majority of the employed population (55% of residents) earns up to 2 minimum wages (2604 Reais or 502 USD, based on values from 6 February 2023) [31].

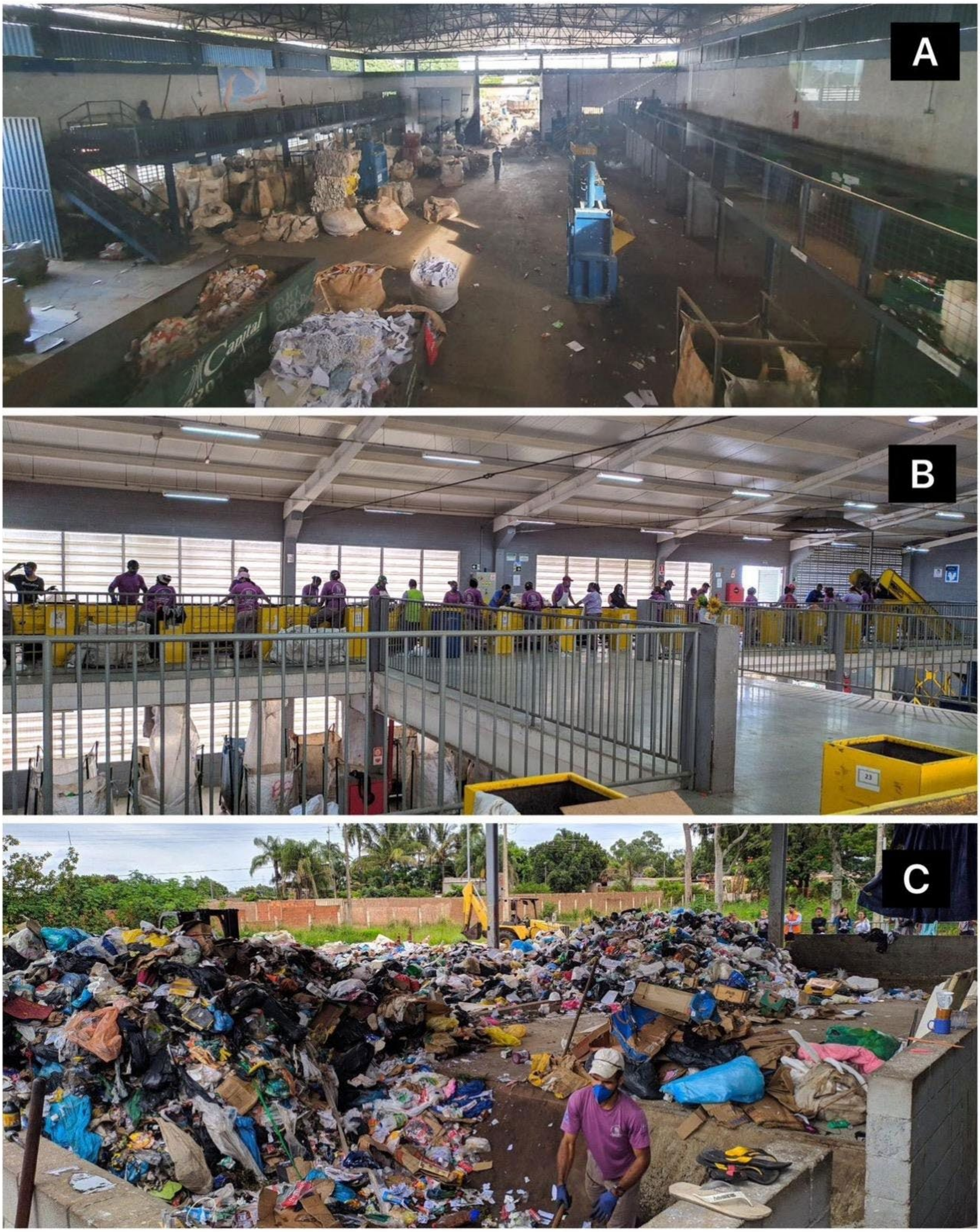

Figure 2. View of the workspaces of the three cooperatives (**A**) *Recicle a Vida* (**B**), *Plasferro* and (**C**) *Coopere*.

2.2. Data Collection

Empirical data gathering at the WPOs involved the collection of secondary gravimetry data of the classified materials (paper, high-density polypropylene (HDPE), low-density polypropylene (LDPE), polyethylene terephthalate (PET), glass, aluminium and steel) and data on energy expenditure during all processes involved with the collection and the machinery used in the handling of the recyclable materials (forklift, conveyer belt, presses, illumination, etc.) in each of the WPOs (inventory data). We also collected additional primary data from the three WPOs on the number of workers, gender, average age and working hours and on reverse logistics projects involving the WPOs. We used secondary sociodemographic data on the waste-generating regions via the reports provided by the three cooperatives. These data are periodically sent to the Urban Cleaning Service in Brasília (SLU) and are published in their annual report [11]. Major information sources were reports, tables and spreadsheets with the types of waste, market value, quantity sold, type of equipment used, hours of operation of the equipment and energy consumption of the equipment used, including the collection trucks, from the year 2019. The data referring to the supply of energy via hydroelectric plants were collected from the *Statistical Yearbook of Electric Energy* of the Energy Research Company (EPE) [32]. The year 2019 was used as a base, given that due to the COVID-19 pandemic, data for the most recent years show inconsistencies.

2.3. Data Analysis

Data analysis involved the methodology designed for small-scale recovery and recycling of solid waste materials and its respective methodological tools of the Clean Development Mechanism (CDM) of the United Nations Convention on Climate Change (UNFCCC). This methodology is also known as AMS-III.AJ.: Recovery and recycling of materials from solid waste [33]. The following three tools were used: (1) a tool to calculate the emission factor for electricity systems, (2) a tool to calculate the baseline emissions and project line emissions and (3) a tool to calculate leaked emissions based on electricity consumption and on emissions generated at the solid waste disposal sites.

These tools are related to electricity consumption, since for the production of consumer goods in both scenarios (baseline and project line), the main source of energy comes from hydroelectric plants, whose operation depends on the flooding of forested areas. Despite appearing to be a source of clean energy, the flooding of tropical forest areas allows the decomposition of these sediments at the bottom of the reservoirs, emitting CH_4-methane [34]. Therefore, for this study, the greenhouse gas emission factors were adopted for hydroelectric energy generation, according to the literature, of 0.2–0.34 kg CO_2-eq./kWh [35].

The tools complement each other in order to calculate the reduction of GHGs from using recycled materials in the production of new goods and products. To calculate the emission reduction, it is necessary to use three variables: A baseline in which only virgin resources are used for production, a project line in which solid waste is recycled and recycled materials are used in production and a line that measures the leaked emissions associated with electricity consumption. By subtracting these variables, we arrive at the GHG emission reduction according to the following equation:

$$ER_y = BE_y - PE_y - LE_y \quad (1)$$

where

ERy = Reduction of emissions per year y (tCO_2 eq);
BEy = Baseline emissions per year y (tCO_2 eq);
PEy = Project emissions per year y (tCO_2 eq) and
LEy = Leakage emissions per electricity consumption per year (tCO_2 eq).

For the calculation of the baseline for recycling, AMS.III-AJ stipulates that emissions related to the consumption of electricity and the use of fossil fuels (see Table 1) for the production of HDPE, LDPE and PET must be taken into account and are obtained by applying the following equation:

$$\mathrm{BE_y} = \Sigma\,[\mathrm{Q_{i,y}} \times \mathrm{L_i} \times (\mathrm{SEC_{Bl,i}} \times \mathrm{EF_{el,y}} + \mathrm{SFC_{Bl,i}} \times \mathrm{EF_{FF,CO_2}})] \tag{2}$$

where

$\mathrm{BE_y}$ = Baseline Emissions per year y ($\mathrm{tCO_2}$ eq $\mathrm{y^{-1}}$);

i = Indexes for the type of material i (i = 1,2,3 for HDPE, LDPE and PET);

$\mathrm{Q_{i,y}}$ = Quantity of type i plastic recycled per year t (t $\mathrm{y^{-1}}$);

$\mathrm{L_i}$ = Adjustment factor to compensate for material quality degradation and material losses in the product manufacturing process using recycled material;

$\mathrm{SEC_{Bl,i}}$ = Specific consumption of electricity for the production of virgin material type i (MWh $\mathrm{t^{-1}}$);

$\mathrm{EF_{el,y}}$ = Emission factor of the electricity generation network, according to the most recent version ($\mathrm{tCO_2}$ $\mathrm{MWh^{-1}}$);

$\mathrm{SFC_{Bl,i}}$ = Specific fuel consumption for the production of type i virgin material (GJ $\mathrm{t^{-1}}$) and

$\mathrm{EF_{ff,CO_2}}$ = $\mathrm{CO_2}$ emission factor for fossil fuel ($\mathrm{tCO_2}$ $\mathrm{GJ^{-1}}$).

Table 1. Correction factors ($\mathrm{L_i}$) and specific electricity consumption variables for production with virgin and recycled resources, $\mathrm{SEC}_{Bl,i}$, $\mathrm{SFC}_{Bl,i}$ and $\mathrm{SEC_{rec}}$ [30].

Material (i)	**Raw Material $\mathrm{SEC}_{Bl,i}$**		**Recycled Material $\mathrm{SEC_{rec}}$**	**Adjustment Factor $\mathrm{L_i}$**
Metal #	6.84		1.78	0.84
Aluminium #	17.6		0.7	0.9–1.0 *
Glass #	4.83		4.19	0.88–1.0 *
Paper and cardboard #	4.98		1.47	0.82
	$\mathrm{SFC}_{Bl,i}$	$\mathrm{SEC}_{Bl,i}$		
PEAD &	4.17	0.83	0.83	0.75
PEBD &	4.17	1.67	0.83	0.75
PET &	4.17	1.11	0.83	0.75

Values #: $\mathrm{SFC}_{Bl,i}$ and $\mathrm{SEC_{rec}}$ [36,37]; Values $\mathrm{L_i}$ [38]), except for paper and cardboard [39] and aluminium [40]. Values &: $\mathrm{SFC}_{Bl,i}$ and $\mathrm{SEC}_{Bl,i}$ standards according to the methodology [41–43].* The adjustment factor can be 1.0 for glass and aluminium because both resources can be fully recycled (closed loop) when producing the same product [44].

For the calculation of the baseline for recycling, AMS.III-AJ stipulates that emissions related to the consumption of electricity and fossil fuels for the production of glass, aluminium, steel, paper and cardboard are obtained by applying the following equation:

$$BE_y = \sum\,[Q_{i,y} \times L_i \times (SEC_{Bl,i} \times EF_{el,y})] \tag{3}$$

where

BE_{vpp} = Baseline emissions per year y ($\mathrm{tCO_2}$/y)

$Q_{i,y}$ = Quantity of material i recycled per year y (t/y)

L_i = Adjustment factor to cover material quality degradation and material loss in the production process of the final product using the recycled material (use 0.88)

$SEC_{Bl,i}$ = Specific consumption of electricity for the production of raw materials (MWh/t).

EF $\mathrm{_{el,y}}$ = Electricity generation network emission factor, according to the most recent version ($\mathrm{tCO_2}$ $\mathrm{MWh^{-1}}$) and

$\mathrm{EF_{ff,CO_2}}$ = $\mathrm{CO_2}$ emission factor for fossil fuel ($\mathrm{tCO_2}$ $\mathrm{GJ^{-1}}$).

For the project line, AMS.III-AJ stipulates that emissions related to the consumption of electricity for the manufacturing of goods and products with recycled materials must be taken into account by applying the following equation:

$$\mathrm{PE_y} = \sum (Q_{i,y} \times SEC_{\mathrm{rec}} \times EF_{el,y}) \tag{4}$$

where

$Q_{i,y}$ = Quantity of material i recycled per year y (t/y);

SEC_{rec} = Specific electricity consumption for a recycled resource (MWh/t) and

$EF_{el,y}$ = Emission factor of the electricity generation network, according to the most recent version ($\mathrm{tCO_2\ MWh^{-1}}$).

Leakage emissions associated with electricity consumption are calculated using the tool to calculate baseline, project and/or leakage emissions from electricity consumption using the following equation:

$$\mathrm{LE_{EC,Y}} = \sum \mathrm{EC_{LE,l,y}} \times \mathrm{EF_{EF,l,y}} \times (1 + \mathrm{TDL_{l,y}}) \tag{5}$$

where

$\mathrm{LE_{EC,Y}}$ = Leakage emissions from electricity consumption per year y ($\mathrm{tCO_2}$/y). Use 0.001–0.0026;

$\mathrm{EC_{LE,l,y}}$ = Net increase in electricity consumption from source l in year y as a result of leakage (use 0.19);

$\mathrm{EF_{EF,l,y}}$ = Emission factor for electricity generation for source l in year y ($\mathrm{tCO_2}$/MWh) (use 0.22–0.38) and

$\mathrm{TDL_{l,y}}$ = Average technical transmission and distribution losses to supply electricity to source l in year y (use 0.03) (default data according to the methodology).

The following section will demonstrate the results based on the data obtained from the three cooperatives, from the primary data search on energy production and from the interviews conducted with key participants.

3. Results

The following table summarizes the socio-economic background and operational data for the three WPOs (Table 2). The WPO with the largest number of members is *Plasferro*, with 85 workers, most of whom are women. The other two cooperatives have similar numbers of members most of which are female. The average age of the waste pickers from the three units is 33 years. As for working hours, *Recicle a Vida* follows the Brazilian standard of 45 work hours per week, while *Plasferro* and *Coopere* operate a total of 75 h per week, with two work shifts. While *Recicle a Vida* operates its own selective waste collection, *Plasferro* receives material only from the garbage collection transferred to the cooperative by SLU and *Coopere* receives material from both the selective waste collection stream and the garbage stream operated by the city.

Recicle a Vida carries out its own collection and is thus able to generate more thorough and complete data. *Coopere* on the other hand, runs two collection trucks and has also two contracts with the SLU department; one of the contracts is to operate the selective collection and the other contract relates to the sorting activity. *Plasferro* does not have a sorting contract, so it only receives mixed garbage, collected from the door-to-door collection, managed by SLU. Thus, in the selective collection contract, *Coopere* receives, on average, only 1/3 of the total number of truckloads from SLU that arrive at the recycling station every week, while *Plasferro* receives the other 2/3 of the material collected.

Recicle a Vida collects 327 tons of recyclable material per year, *Coopere* receives 1237.75 tons and *Plasferro* receives 1309.01 tons. While *Plasferro* and *Coopere* receive significantly more material during one year, they also have extremely high rejection rates (material that is considered not recyclable, mostly due to contamination) (80.3% and 75%, respectively).

Table 2. Differences in cooperative membership and work conditions in 2019.

	Cooperative Name		
Characteristics	***Recicle a Vida* (A)**	***Plasferro* (B)**	***Coopere* (C)**
Number of workers	85	100	65
Average age (in years)	38	40	37
Women (%)	56	61	54
Total working hours per week	45	75 (2 work shifts)	75 (2 work shifts)
Source of material	Recyclables from selected businesses, neighborhoods, public departments	Recyclables from selected neighborhoods, using a truck owned by *Plasferro* and mixed solid waste collected by SLU	Mixed solid waste collected by SLU
Type of work	Collection and sorting	Collection and sorting	Sorting
Type of contract	No contract	Contract with SLU for collection and sorting	Contract with SLU for sorting
Source of the recyclable material	Operates own selective waste collection	Receives material from garbage collection transferred by SLU	Receives material from both the selective waste collection and the garbage collection operated by SLU
Material separated per year (in tons)	327	1309.01	1237.75
Facility	Own property	SLU owned property	SLU owned property
Rejected material (%)	16.6	80.3	75.3

These two cooperatives work in the same space, at the Waste Recovery Facility, located in the administrative region of Ceilândia, a space made available by the government of the Federal District. These two cooperatives have established an agreement for the recycling of HDPE and LDPE, with *Coopere* working only with LDPE and *Plasferro* only with HDPE. For the other materials, each of these two cooperatives works according to their contract with SLU (Table 3).

Table 3. Quantity of recycled material, in tons, in 2019, by each cooperative.

Cooperative **Type of Material**	***Recicle a Vida* (A) (T)**	***Plasferro* (B) (T)**	***Coopere* (C) (T)**
PEAD	22.5	127.57	0
PEBD	19	0	47.33
PET	20	209.38	142
Paper and cardboard	208	709.52	726.73
Glass	28	161.79	195.03
Aluminium	2.6	0.3	45.39
Steel	27	100.45	81.27
Total	327	1309.01	1237.75

Source: data from the gravimetry report of the respective cooperatives.

The following considerations had to be taken into account when calculating the amount of fuel consumed by the processes involved in the collection of recyclable materials. We used the maximum quantity of diesel used by the trucks (on average consuming 3.5 L/km) because usually the trucks travel with loads of material and they tend to stop frequently along the way, which causes them to consume a greater amount of fuel (see Table 4). The distances traveled for the recycling program in Brasília is on average 7280 km/month; therefore, the ratio of 1 to 3 km was used for *Coopere* and 2 to 3 km for *Plasferro*. For *Coopere*'s fuel calculation, it was necessary to further add the value for the cooperative's own two trucks used for its own collection all year round. In addition, we also considered the amount of LPG gas used by the forklifts to move around recyclable materials in all three cooperatives. For that purpose, we converted the LPG gas to diesel oil, applying the following conversion: 1 m^3 of LPG = 0.64 m^3 of diesel.

Table 4. Annual energy consumption by each cooperative, in 2019.

Cooperative	Fuel (m^3) (Diesel and LPG in m^3)	Eletricity (GWh)
Recicle a Vida (A)	5.182 m^3	0.045 GWh
Plasferro (B)	21.147 m^3	0.028 GWh
Coopere (C)	20.806 m^3	0.028 GWh

The energy consumption by each cooperative, during 2019, was also accounted for, as described in Table 4, taking into account all the machines used in the recycling process: moving belts, presses and grinding machines.

The amount of rejected materials (non-recyclable and considered waste) that arrive at the cooperative must also be captured in order to address the level of contamination that enters the cooperative. This material is separated as rejected material and has to be sent to the sanitary landfill (Table 5). In 2019, *Recicle a Vida* (A) generated on average 16.6% of materials considered waste, compared to 80.3% by *Plasferro* (B) and 75.3% by *Coopere* (C). Since these two cooperatives reported a similar proportion of recyclable versus rejected materials, we used the same proportion to calculate fuel consumption (1/3 *Coopere* (C) and 2/3 *Plasferro* (B)), taking into account the number of employees and materials processed by each one. The significant difference in the quantity of waste generated between *Recicle a Vida* (A) and the other two cooperatives can be explained by the quality of the material collection. While *Recicle a Vida* (A) receives its material from selective waste collection for recycling, the other two cooperatives receive their material from the regular waste collection.

Table 5. Level of contamination of recyclable material that reaches the cooperative.

Cooperative	Rejected Materials (in Tons)/Year
Recicle a Vida (A)	65.36
Plasferro (B)	4015.20
Coopere (C)	2007.60

Tables 6–8 show three different scenarios for each of the three WPOs: (1) base emissions (BE), which demonstrates what the situation of greenhouse gas emissions would be like without recycling and with a production process that uses exclusively virgin resources; (2) project emissions (PE), which demonstrate the real situation, in which a certain amount of materials is recycled by each cooperative and this material is incorporated into the production process through reverse logistics and (3) reduced emissions (RE), which are a result of subtracting BE by PE, thus obtaining the differential between the two scenarios. Therefore, it is possible to verify in Tables 5–7 how many GHG emissions have been avoided by recycling by each cooperative. It is worth mentioning that for each line of calculation, two factors of carbon emissions at the hydroelectric power plants were taken into account: $EF_{el,y}$ = 0.22 and 0.38.

As for emissions in absolute numbers measured in tons, *Coopere* (C) managed to reduce between 783.8 and 1267.2 tons of carbon (Table 6), which is equivalent to 61.6% to 60% of the emissions generated in 2019. *Plasferro* (B) created a reduction of 705.4 to 1064.1 tons of CO_2 (Table 7), equivalent to 56.2% to 59.5% of CO_2 carbon emissions from its waste. *Recicle a Vida* (A) produced a reduction of 192.6 to 304.6 tons of CO_2 carbon in 2019 (Table 8), equivalent to 62.5% to 60.4% of the emissions generated in 2019.

Table 6. Reduction of greenhouse gas emissions, in 2019, in tons, by *Coopere*.

$EF_{el,y}$ (tCO_2/MWh)	**0.22**	**0.38**	**0.22**	**0.38**	**0.22**	**0.38**
Type of Material	**Baseline Emissions BEy**		**Projected Emissions PEy**		**Emission Reduction ERy**	
PEBD	42.8	52.3	8.6	14.9	34.2	37.4
PET	115.4	134.3	25.9	44.7	89.5	89.5
Paper and cardboard	652.8	1127.7	235.0	405.9	417.8	721.7
Glass	182.3	315.0	179.7	310.5	2.5	4.4
Aluminium	175.7	303.5	6.9	12.0	168.7	291.4
Steel	102.7	177.4	31.8	54.9	70.9	122.4
Total	1272.0	2110.4	488.1	843.2	783.8	1267.2

Table 7. Reduction of greenhouse gas emissions, in 2019, in tons, by *Plasferro*.

$EF_{el,y}$ (tCO_2/MWh)	**0.22**	**0.38**	**0.22**	**0.38**	**0.22**	**0.38**
Type of Material	**Baseline Emissions BEy**		**Projected Emissions PEy**		**Emission Reduction ERy**	
PEAD	97.8	110.5	23.2	40.2	74.5	70.3
PET	170.2	198.1	38.2	66.0	132.0	132.1
Paper and cardboard	637.4	1101.0	229.4	396.3	407.9	704.6
Glass	151.2	261.3	149.1	257.6	2.1	3.7
Aluminium	1.1	2.0	0.0	0.0	1.1	1.9
Steel	126.9	219.3	39.3	67.9	87.6	151.3
Total	1184.9	1892.3	479.5	828.2	705.4	1064.1

Table 8. Reduction of greenhouse gas emissions, in 2019, in tons, by *Recicle a Vida*.

$EF_{el,y}$ (tCO_2/MWh)	**0.22**	**0.38**	**0.22**	**0.38**	**0.22**	**0.38**
Type of Material	**Baseline Emissions BEy**		**Projected Emissions PEy**		**Emission Reduction ERy**	
PEAD	17.2	19.4	4.1	7.0	13.1	12.4
PEBD	17.2	21.0	3.4	5.9	13.7	15.0
PET	16.2	18.9	3.6	6.3	12.6	12.6
Paper and cardboard	186.8	322.7	67.2	116.1	119.5	206.5
Glass	26.1	45.2	25.8	44.5	0.3	0.6
Aluminium	10.0	17.3	0.4	0.6	9.6	16.6
Steel	34.1	58.9	10.5	18.2	23.5	40.6
Total	307.9	503.7	115.2	199.1	192.6	304.6

The percentage described in the next Table (Table 9) demonstrates how many GHG emissions were reduced with recycling by each individual type of material, in each cooperative, expressed as tons reduced in ER per type of material times 100 divided by the total tons emitted in BE per type of material; according to the equation $\frac{ERi \times 100}{BEi}$, where i is the type of material.

Table 9. Percentage of reduced greenhouse gas emissions, in 2019, in tons, by cooperative.

$EF_{el,y}$ (tCO_2/MWh)	**0.22**	**0.38**	**0.22**	**0.38**	**0.22**	**0.38**
Type of material	***Recicle a Vida***		***Coopere***		***Plasferro***	
PEAD	76.1	63.5	0	0	76.1	63.6
PEBD	79.8	71.4	79.8	71.4	0	0
PET	77.5	66.6	77.5	66.6	77.5	66.6
Paper and cardboard	64.0	64.0	64.0	64.0	64.0	64.0
Glas	1.41	1.41	1.4	1.4	1.4	1.4
Aluminium	96.0	96.0	96.0	96.0	95.9	95.9
Steel	69.5	69.01	69.0	69.0	69.0	69.0
Total	62.5	60.4	61.6	60.0	59.5	56.2

4. Discussion

The initial warning about climate problems related to the greenhouse effect caused by humans as a consequence of a steady increase in carbon emissions into the atmosphere was issued for the first time in 1950 [6]. Since then, efforts have been made to analyze the escalation of the greenhouse effect and to seek solutions that can reduce carbon dioxide emissions. Selective waste collection, recycling and reverse logistics are important measures that reduce GHG emissions and help mitigate climate change [45].

4.1. Waste Picker Cooperatives—Agents for GHG Emission Reduction

Our study shows that the work of waste pickers can reduce CO_2 emissions by 59% to 62% in one year (Table 9). This scenario was also identified in the 2013 study by King and Gutberlet [3], conducted in Ribeirão Pires, in which the cooperative *Cooperpires* recorded a 60% to 62% reduction in greenhouse gas emissions. Similar research was carried out with the cooperative *Montesul* (*Associação Montes Claros de Catadores de Recicláveis*), which is responsible for the selective waste collection and classification in 37 neighborhoods in the city of Montes Claros, in the state of Minas Gerais, and shows that a reduction of 325 tons of CO_2 was recorded in a period of only five months [27]. In our study, we compare three different cooperatives, each one receiving different amounts of materials and different qualities of materials.

It is possible to analyze and determine the emission reduction from recycling, expressed in the percentage of emissions avoided. *Recicle a Vida* (A) is the cooperative that recorded the highest percentage of reduction in carbon emissions (62.5% to 60.4%) and also presents the lowest proportion of rejected material (16.6%). We infer that the quality of the material, when collected by this cooperative, has a lower level of contamination, allowing a greater proportion to be recycled. Although the consumption of electricity, coming from hydroelectric power plants, is greater for this cooperative, the quality of its materials provided a greater reduction of GHG emissions. The higher quality of the material can be associated with the educational activities carried out by this cooperative in the neighborhoods serviced by them. The waste pickers are recognized by the population, which invests time and effort in separating their waste properly, becoming a key differential for a successful recycling program.

In relation to the reduction of GHG emissions, the results of the other two cooperatives are similar. This may be due to the high amount of material they receive and the lower use of electricity spent in their processes. However, the separation processes in place are not efficient and generate large amounts of waste; 75 to 80% of all materials that enter these two cooperatives still have to be sent to the landfill. This is a major challenge that could be addressed by implementing continuous environmental education campaigns and instructing households on clean source separation.

In 2019, the Brasília landfill received 800,000 tons of waste; the work of the waste pickers in these three cooperatives has managed to prevent an additional 2873.76 tons of non-biodegradable material from being added to that amount. The work of waste pickers is essential to extend the life of the landfill and to reduce the impacts that waste has on the environment and the climate. Therefore, it would be interesting to conduct a larger study to measure the GHG emission reductions in all cooperatives operating in the district. However, these other cooperatives do not yet collect data on the different materials they separate, they only keep track of the total monthly quantity of materials separated. In order to get a precise picture of the GHG emission reductions and energy savings, WPOs need to invest in keeping a regularly updated inventory on the quantity of incoming materials, the rejected materials as well as separated materials by different types.

4.2. Environmental Contributions of Waste Picker Cooperatives

While recycling is not the final solution to our waste dilemma, it is a process that enables lower production costs and often generates less environmental degradation compared to virgin resource extraction. For example, the production of one ton of plastic uses

7000 kWh of energy and generates 5313.96 kg CO_2 emissions [46]. Recycling one ton of plastic, according to the data from this study, uses an equivalent of 137 kWh, which means 6863 kWh less energy is spent with recycling than with the production using raw material. This type of analysis based on carbon emission studies has produced data supporting the adoption of policies in favor of the circular economy, as they demonstrate the potential contribution to more sustainable development, with products and materials following a cyclic instead of a linear pathway in the production of new consumer goods.

4.3. Remaining Challenges

As mentioned earlier, keeping a regular inventory still remains a key challenge in some of the WPOs and particularly among autonomous waste pickers. Despite the benefits associated with the environmentally appropriate disposal of recyclable solid waste, reduced disposal in landfills and lower demand for natural resource extraction, as well as evidence of reduced greenhouse gas emissions through the application of the UNFCCC's AMS-III.AJ [41–43], there is a major barrier to converting these results into economically viable payments for the environmental services provided by WPOs [47].

Through the contributions to mitigate climate change and the development of process and infrastructure improvement projects, known as Project Design Documents (PDDs), it is possible to establish data and criteria for validating the additionality of these emission reductions, which is calculated after verifying the total emissions reduced minus the emissions of greenhouse gases from a project [48], thereby allowing us to understand whether emissions mitigation is truly additional. Thus, it is possible to design the PDDs, where the process of benefits and efforts related to emission reduction should be implemented, monitored, validated, registered and certified after its final verification, thus enabling the issuance of carbon credits or green bonds [49,50].

4.4. Certification for GHG Emission Reductions

The development and certification processes and audits associated with the approval of these projects, whether in the regulated market defined by federal and international regulations or in the voluntary carbon credit emission market [47], remain exclusively accessible to a specific niche of consultants and auditing companies. High costs of the training, development, registration, validation and verification process make small-scale projects challenging, as their volume of GHG emission reductions compared to large-scale projects is much lower, which means that issuing carbon credits or green bonds is not attractive to these auditors and consultants [46]. The following table (Table 10) shows the yearly estimated values each WPO would receive for their work in 2019.

Table 10. Potential profit value obtained in a possible sale of carbon credits at present value (February 2023), in US dollars, by cooperative.

1 tCO_2e = 1 Carbon Credit	**$EF_{el,y}$ = 0.2**	**Estimated Commercial Value USD 4.69/Credit**	**$EF_{el,y}$ = 0.38**	**Estimated Commercial Value USD 4.69/Credit**
WPO	Credit Unit	USD	Credit Unit	USD
Coopere	783.8	3676.02	1267.2	5943.17
Plasferro	705.4	3308.33	1064.1	4990.63
Recicle a Vida	192.6	903.29	304.6	1428.57

Source: Allied Offsets—price by project type: waste disposal—https://alliedoffsets.com/directory/ (accessed on 19 March 2023).

Registration, verification and validation costs on voluntary market platforms such as Gold Standard or Verra exceed USD 9000 per project [51,52], which makes the financial viability of small-scale emission reduction projects difficult due to these high costs. Moreover, there are costs associated with hiring specialized companies to develop the PDDs, which can further hinder the viability of the project [48], as well as the need to connect credit-issuing organizations with organizations and investors interested in purchasing these environmental compensation mechanisms to mitigate their GHG emissions.

However, the significance of the waste pickers' contribution to reducing GHG emissions lies in the scale of their operations, since they are present in almost every city throughout the country. Their collective effort has to be formally recognized, accounted for and remunerated. This would make a difference to their livelihoods and working conditions.

Currently, the Brazilian Congress is considering Bill 412/2022 [53], which establishes a regulated emissions reduction market that could make high-value carbon credits viable for small-scale projects, with high social and environmental impacts; however, they must consider simplifying the validation process to ensure that the gains from the sale of these environmental assets cover the costs of developing and approving these projects. An alternative that could enable the issuance of carbon credits or green bonds is through projects that aggregate multiple organizations, such as networks of WPOs, thus allowing for a significant increase in the volume of materials directed towards recycling [54] and, consequently, the potential volume of carbon credits generated. Nevertheless, the negotiation and management of resources requires the centralization of these transactions between environmental assets and interested organizations, which demand good management practices and transparency throughout the process.

The national movement of waste pickers in Brazil (MNCR—Movimento Nacional dos Catadores(as) de Materiais) and their National Association of Waste Pickers (ANCAT—*Associação Nacional de Catadores e Catadoras de Materiais Recicláveis*) could be a potential organization to assess the quantities of materials diverted from landfilling and incineration to apply for carbon credits for the work of these tens of thousands of waste pickers in Brazil.

5. Conclusions

The study confirms that solid waste recycling with waste picker organizations contributes to the guidelines of the National Policy on Solid Waste and the National Policy on Climate Change, thanks to the 60% reduction in carbon dioxide emissions over the period of one year that these organizations have achieved. WPOs are fundamental for environmental preservation, for making economic and social development compatible with the protection of the climate system and for achieving the commitments established by the Kyoto Protocol.

This study indicates that individual and small-scale WPOs projects that use the AMS-III.AJ methodology may not be economically viable due to current market criteria, as well as the verification parameters of the methodology. WPOs need to organize into larger projects in order to be contemplated for carbon credits. The evolution of the methodology is necessary to allow for the inclusion of WPO projects, together with the possible development of a new carbon certification standard focused on recycling and the implementation of public policies that enable smaller projects to access the carbon credits and the green bond market. In the meantime, WPOs can collaborate as networks, associations, federations or social movements in order to accumulate the necessary quantities of materials directed towards recycling, which would allow them to access carbon crediting schemes.

The handling and management of solid waste, in Brazil, still has a long way to go to effectively recover materials for the circular economy and to reduce environmental and climate impacts. Most people forget that achieving a better waste management system depends on those individuals and groups of workers directly involved in urban waste management, the waste pickers. This study also evidences that those WPOs that conduct door-to-door collection of recyclable materials receive a better material quality, with much less waste mixed among the recyclables. This fact demonstrates that involving waste pickers in the collection allows them to interact with households, educating them about clean source separation, which improves the waste pickers' income, reduces the amount of rejected materials that need to be transported to the landfill and, in the end, reduces GHG emissions. It is necessary to conduct similar studies to allow for the quantification of the impacts and benefits of recycling and to demonstrate how integrating WPOs into waste management increases material diversion and recycling, ultimately helping governments progress towards the achievement of sustainable development goals and climate change mitigation.

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