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Systems analysis of packaging HDPE plastic recycling chain – an informal sector circular economy case in Brazil, Global South: Stakeholder dynamics, material quality, rejects and value appropriation

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Abstract

We uncover the systemic complexities of a polymer recycling chain insufficiently investigated, focusing on high-density polyethylene (HDPE) – a core contributor to plastics pollution in the Global South, via mismanaged waste. Rigid blow-moulded HDPE is widely used in retail packaging and fast-moving consumer goods containers; it is also sought-after for the production of 'secondary', recycled HDPE (r-HDPE). Starting from a single location (Brazilian town) and a waste picker cooperative (informal recyclers – IRS), we investigate the collection/sorting of municipal solid waste (MSW) recyclables along the downstream value chain of scrap dealing, reprocessing, and manufacturing. The methodological frameworks of technical networks, material flow analysis (MFA), and complex value optimization for resource recovery were used. Results demonstrate an informal to formal spectrum of operations, with clear transition points. The material quality standards required at manufacturing with r-HDPE are poorly applied at the collection stage, indicating a problematic quality management interfacing. Material rejects (losses), allowable contamination level, and monetised value of recyclate are interlinked at each stage. The most substantial value creation and appropriation is accomplished at the initial collection/sorting waste picker stage, followed by the value creation at the final production of the r-HDPE pellet. Reprocessors bear disproportionate material losses, counterbalanced by purchasing pricing. Despite overall rejects of 29% wt.$_{(ar)}$, a high actual recycling rate for rigid HDPE is achieved: 38% wt.$_{(ar)}$, indicative of an effective collection for recycling and refined manual sorting by the partially formalised IRS. These novel insights on informal recycling networks can inform effective interventions to expand circularity and prevent plastic pollution.

Highlights

- Specialised roles in the HDPE recycling value chain are detailed, stating informality to formality transition
- Value creation and appropriation, material losses (rejects), and pricing are highly interconnected
- Quality standards for r-HDPE poorly communicated / applied to early value chain / IRS
- Despite the limitations, a high actual recycling rate is achieved for rigid HDPE: ca 38% wt.$_{(ar)}$

Introduction

Plastics have been a key material of choice for the last few decades in all aspects of the economy (OECD, 2022). As a material and applied in products, it is now widely investigated through the new lenses of avoiding plastic pollution (Jambeck et al., 2015; Lau et al., 2020; Velis et al., 2023) – an emergent global challenge of our times (UNEP, 2023) – and enabling a circular economy (Cook et al., 2022) by delivering resource efficiency (Braungart et al., 2007). It is increasingly targeted for recycling by both formal waste management systems and informal waste workers across the Global South economy (Al-Salem et al., 2009; Cook et al., 2024; Ezeah et al., 2013). Recycling is, in fact, performed in a system consisting of multiple stages – a value chain or industrial 'ecosystem'.

Several studies on recycling value chains for various materials have been carried out globally, such as in Indonesia (Sembiring and Nitivattananon, 2010), the Philippines (Scheinberg et al., 2011), India (Kumar et al., 2018; Nandy et al., 2015; Sandhu et al., 2017; Suthar et al., 2016), China (Steuer et al., 2017), Bangladesh (Mourshed et al., 2017; Siddique et al., 2022), Egypt (Jaligot et al., 2016), and Peru (Torres and Cornejo, 2016). None of these studies have used multiple analytical tools, focused on HDPE, or conducted a comprehensive recycling chain analysis that includes interaction and trade-offs between stakeholders.

Specifically in Brazil, Coelho et al. (2011) reported the presence of scrap dealers and waste pickers in the recyclable polyethylene terephthalate (PET) recycling chain; in 2007, waste pickers in Rio de Janeiro collected materials at the city's dumpsite and commercialised to the rest of the chain, including dealers, cooperatives of waste pickers and recyclers (Pacheco et al., 2012). Rutkowski and Rutkowski (2017), in their field research, estimated that paper and plastics represent 79% of waste pickers' income, having a substantial national recycling market demand: indeed, currently, it seems that at large, Brazil does not export its plastic waste due to its recycling domestic market operating under capacity. Pimentel Pincelli et al. (2021) presented an overview of Brazilian plastic packaging waste (PPW) management, identifying that 12 Mt of PPW was generated in 2017, 1% wt. being formally collected separately from the mixed (selective) collection and 3.5% wt. being informally collected; therefore, 4.5% wt. recycled mechanically.

However, insufficient information is available on the plastic recycling industry in the country and the complexities of its value chain (Conke, 2018; Rebehy et al., 2019). Research in the field has been highlighted as important in supporting improvements in public policies for circular economy systems for post-consumption packaging (Guarnieri et al., 2020; Pimentel Pincelli et al., 2021). There is a need to map the stakeholders involved in the chain, quantify the mass and monetary flows systematically, and evaluate how value is created and destroyed along the chain with possible interventions. 'Complex value' refers to measurable benefits (positive) and impacts (negative) in the environmental, economic, social, and technical domains, denoting potential trade-offs in such a system (Iacovidou et al., 2017a).

Here, we aim to document and assess the recycling value chain of a specific material type of plastic as part of a circular economy system, from waste generation to the production of secondary materials. Specifically, this study (1) explores the typical stakeholders involved in a recycling chain in Brazil and their roles; (2) investigates the detailed material and monetary flows in this chain; and (3) navigates the evolution of complex value changes throughout the chain in four domains (environmental, technical, social, and economic), considering the relevant trade-offs.

Plastic recycling value chains in Brazil can be complex due to the multiplicity of organisations and substantial geographical distances involved. Therefore, to be able to disentangle the complexities, a single specific geographical/administrative area of plastic waste arisings and a single type of recyclable plastic packaging were selected and identified for in-depth analysis (case study) as the specific starting point for such a value chain. The municipality of Cachoeira de Minas, in Southeast Brazil, was selected because it can be perceived as a successful case in the sense that the city achieved to close the local dumpsite and was also able to assist waste pickers (informal waste workers) in forming an association to perform an at-source-separated recyclable wastes collection and subsequent sorting – actions suggested as core to improving waste management (Wilson, 2023). Specifically, the authorities, based on the Brazilian National Solid Waste Policy (Federal Law No. 12305/2010) (Brazil, 2010), granted the local association with an exclusive right to provide recyclables collection services to the entire city, including urban and rural areas. Therefore, it can be considered as a representative example of such enabling interventions towards inclusivity and empowerment of informal waste worker activities (Just Transition) (Cook et al., 2024; Shift, 2022) and wider partial formalisation at the starting location of a plastics recycling value chain in cooperatives or associations (Gutberlet, 2012).

The scope is further narrowed to only one currently under-explored sub-category of plastics typical of fast-moving consumer goods (FMCG). We study the recycling chain of high-density polyethylene (HDPE) present in municipal solid waste (MSW), which has not been sufficiently studied before, as most research historically has been focusing on polyethylene terephthalate (PET), with just a few mentions of HDPE and other polymer types, as in Jaligot et al. (2016). We further focus and assess in-depth this recycling chain case study on blow-moulded rigid HDPE plastics, used for rigid hollow objects (non-transparent containers), such as milk and juice bottles, shampoos, cleaning products, etc. (British Plastics Federation, 2024), because it is far more common than injection-moulded on a mass basis. Additionally, it is the main material of choice for producing recycled HDPE (r-HDPE). HDPE is widely used in Brazil for multiple applications, such as packaging for food, hygiene and cleaning products, toys, and other domestic products (Abiplast, 2022). Rutkowski and Rutkowski (2017) showed that after PET, HDPE features the biggest recyclable plastic market in Brazil. Furthermore, from all MSW in the year 2016 in Cachoeira de Minas, HDPE is the plastic type that contributed the most to the revenue for the local waste pickers association (Oliveira, 2018), which states its importance for the region.

Materials and Methods

3.1 Case Study Specificities

The methodological approach comprises a single case study of recyclable plastic items made from one polymer and item formulation process; and interpreting data through a combination of analytical tools. A case study is approached here as an in-depth investigation to comprehend a phenomenon or test a specific theory/ model (Yin, 2012). This approach allows the investigation of complex phenomena through contextual analysis, exploration of multiple source data, application of theories, and even extension of existing methodologies (Stake, 2011). We support that the single case study design is well suited to the explorative nature of the study, allowing it to illustrate in detail complex dynamics – specifically, those of the recycling value chain. Therefore, depth of analysis was prioritised here over the multiplicity of cases and statistical analyses. This was made feasible using multiple analytical frameworks and detailed data scrutiny, which would have been difficult to achieve for multiple cases or a large sample thereof.

Regarding the starting location, the Brazilian city Cachoeira de Minas has 11,884 inhabitants, according to the most recent census (IBGE, 2022). The regional GDP per capita was R$ 24,207.36 per year (equivalent to US$ 6,247.06 per year) in 2018. According to Oliveira (2018), the daily municipal waste generation per capita was 0.67 $kg.day^{-1}.inhabitant^{-1}$ (or 245 $kg.year^{-1}.inhabitant^{-1}$) in 2016. That is 65% of Brazil's average municipal solid waste generation per capita, estimated at 1.032 $kg.day^{-1}.inhabitant^{-1}$ in 2016 (Abrelpe, 2017).

3.2 Data Collection

Data were gathered during a 15-month period through desk and field research and were of qualitative and quantitative nature. The desk-based research included a literature review specific to the case study (i.e., HDPE and Cachoeira de Minas municipality) and documental research. Documental research included gathering official records available online from the Cachoeira de Minas city council. Field research included four semi-structured interviews, two conducted by phone (due to COVID-19 pandemic lockdowns) and two conducted in person (the interview guide used is provided in the **Supplementary Material (SM)** – Section 1: **S1**). On-site evidence and data collection included two field visits to the Association of Waste Pickers in Cachoeira de Minas and to one reprocessing company in the state of Sao Paulo, where besides the interview, observational data was collected concerning operations (**Observation template in SM – S2**), photographic evidence included.

3.3 Data Tools and Analytics

All data were reviewed, transcribed, and organised into a database (Microsoft Excel©) and prepared to perform a crossover analysis where different 'lenses' on qualitative and quantitative data sets were used, along with a suite of analytical tools, in line with Grbich (2013). Three analytical tools and/or frameworks (A-C) were used here, **A**: 'Complex Value Optimisation for Resource Recovery' (CVORR); **B**: 'Solid Waste Technical Network framework' (SWTN); and **C**: 'Solidary Selective Collection of Solid Waste' (SoCo). To date, these have been applied in waste management and resources recovery/ circular economy systems separately.

CVORR is a systems thinking approach where 'value' is perceived and quantified as a complex variable with positive and negative impacts in multiple dimensions that change dynamically within a system (Iacovidou et al., 2017a, 2017b; Millward-Hopkins et al., 2018). In sum, after selecting the system and boundaries, a material flow analysis (MFA) (Brunner and Rechberger, 2016) is conducted to describe the system on a mass basis (preserved property), followed by the selection of wider value metrics and complex value quantification. The CVORR approach was used here as a generic analytical framework.

To complement and specify the CVORR approach, we used the SWTN (Fiore, 2013; Fiore and Rutkowski, 2017), which originated from the 'Technical Networks' social sciences theory (Santos, 1994). SWTN was used here to map: (1) the case study stakeholders and dissect the dynamics between them; (2) the geographic location of the facilities where they act (nodes); and (3) the flows materialising between them (material, monetary, and informational flows).

Stakeholders were divided into (1) *direct*: those who directly affect the generation and management of recyclable waste materials by being involved in their production and recycling, i.e., handling the actual materials; and, (2) *indirect*: those who influence, indirectly via decision-making, or are influenced by the generation and management of recyclable waste materials, but are not engaged in the mass or monetary transactions accrued in the recyclables' supply chain. Typical indirect stakeholders (also often referred to as 'secondary stakeholders') may include governments, nongovernmental organisations, research institutes, local/regional/national/international consultants, and the media (de Oliveira et al., 2019).

Geographical locations of nodes were documented via geographical information systems (GIS) software (version: 3.12.0) (QGIS, 2023) stating the facilities of stakeholders identified in the research, using the reference system DATUM SIRGAS 2000. Notably, material flows are common to both CVORR and SWTN, documented via MFA diagrams (Brunner and Rechberger, 2016; Cencic and Rechberger, 2008). Software STAN, short for 'Substance flow analysis' - version 2 (TU Wien, 2012) was used for visualization and mass balance calculations. MFA calculations and assumptions are detailed in **SM** – **S3**.

The wider CVORR framework introduces 'dimensions' of value flowing through the systems, grouped into environmental, social, economic, and technical aspects for practical reasons. The specific variables for quantifying such values were informed by the SoCo tool (Sakamoto et al., 2021; Velis et al., 2016), listed along with definitions in **Table S2** in **SM – S4**. This approach allows the identification of trade-offs in value between processes and stakeholders in the system and attempts to consider system-wide improvement interventions holistically. Trade-offs are perceived here as a balance between separate potentially incompatible key features of a system. For example, there is a potential increase in negative social impacts when trying to achieve higher recycling rates by exporting to places with very low environmental and health and safety standards (Velis, 2015). Besides identifying and describing the value trade-offs, a recovery for recycling, material reject, and value appropriation analyses were conducted, inspired by the work of Lankford et al. (2020), and using the equations explained below.

Material rejects denote here the mass of resources that are not used by a certain stakeholder *i* in the chain and, therefore, do not hold value to this stakeholder – they become (solid) waste. The mass balance is observed in **Eq. (1)**.

$$c_i = d_i - r_i \quad \textbf{Eq. (1)}$$

Where: for each stakeholder *i*, c_i is the mass of recyclate sold to the stakeholder upstream of the recycling chain (Mg) – flows F11, F12 and F13 in **Figure S1** of **SM** – **S3**; d_i is the mass of recyclate bought from the stakeholder downstream of the recycling chain (Mg) – flows F2, F11 and F12 in **Figure S1** of **SM** – **S3**; and r_i is the mass of recyclate rejects not used by stakeholder *i* (Mg) – flows F17, F18 and F19 in **Figure S1** of **SM** – **S3**.

The *Material Recovery for Recycling Proportion* (MRRP) *for each stakeholder* is then calculated by assuming that if materials are not rejected, they are recovered and proceed through the recycling chain, as in **Eq. (2)**.

$$MRRP_i\,(\%) = \frac{c_i}{d_i} * 100 \text{ Eq. (2)}$$

Where: $MRRP_i$ is the Material Recovery for Recycling Proportion for stakeholder *i* (%); c_i is the mass of recyclate sold to the stakeholder upstream of the recycling chain (Mg) – flows F11, F12 and F13 in **Figure S1** of **SM** – **S3**; and d_i is the mass of recyclate bought from the stakeholder downstream of the recycling chain (Mg) – flows F2, F11 and F12 in **Figure S1** of **SM** – **S3**.

The overall MRRP (for the entire recycling chain) was calculated by the mass of recyclate sold by the reprocessor (and bought by the product manufacturer) divided by the total mass of the HDPE waste generated within the system boundaries (system input), in this case, the total rigid HDPE material in the city of Cachoeira de Minas, assuming no material stock stays with the consumers within the one year time boundary due to single-use nature of most rigid HDPE products, as in **Eq. (3)**.

$$MRRP\,(\%) = \frac{e}{f} * 100 \text{ Eq. (3)}$$

Where: *MRRP* is the Material Recovery for Recycling Proportion (%); *e* is the mass of recyclate sold by the reprocessor and bought by the product manufacturer (Mg) – flow F13 in **Figure S1** of **SM** – **S3**; and *f* is the total mass of the recyclate waste generated in the system boundaries (Mg) – flow F16 in **Figure S1** of **SM** – **S3**.

Therefore, the *Material Reject Proportion* (*MRP*) for each stakeholder was calculated by dividing the total mass of material rejects by the total processed materials by each stakeholder (total materials bought), as in **Eq. (4)**.

$$MRP_i\ (\%) = \frac{r_i}{d_i} * 100 \text{ Eq. (4)}$$

Where: for each stakeholder *i*, MRP_i is the Material Reject Proportion (%); r_i is the mass of recyclate rejects not used by stakeholder *i* (Mg) – flows F17, F18 and F19 in **Figure S1** of **SM** – **S3**; and d_i is the mass of recyclate bought from the stakeholder downstream of the recycling chain (Mg) – flows F2, F11 and F12 in **Figure S1** of **SM** – **S3**.

The overall MRP across the entire recycling system was calculated by the sum of mass of rejects in each stakeholder of the recycling chain, divided by the total mass of the recyclate under study collected for recycling, as in **Eq. (5)**.

$$MRP\,(\%) = \frac{\sum_{i=1}^{n} r_i}{t} * 100 \text{ Eq. (5)}$$

Where: MRP is the overall Material Reject Proportion (%); n is the number of stakeholders in the recycling chain; r_i is the mass of recyclate rejects not used by stakeholder *i* (Mg) – flows F17, F18 and F19 in **Figure S1** of **SM** – **S3**; and *t* is the total mass of recyclate collected for recycling (Mg), before going to the sorting stage – flow F2 in **Figure S1** of **SM** – **S3**.

Value Appropriation (*VA*), in this context, refers to the economic value obtained from the material that is being processed by each consecutive stakeholder of a recycling chain that handles the material. It was calculated here by the relative difference between the price sold and the price bought of the recyclable good (i.e., the recyclate) within the operations of a stakeholder (i.e., at process input and output stages), expressed as a percentage, as defined in **Eq. (6)**.

$$VA_i\,(\%) = \frac{a_i - b_i}{b_i} * 100 \quad \textbf{Eq. (6)}$$

Where: for each stakeholder *i*, *VA* is the Value Appropriation (%); a_i is the price that the stakeholder sold one kg of recyclate to the stakeholder upstream of the recycling chain (US$.kg^{-1}); and b_i is the price that the same stakeholder bought one kg of the same recyclate from the stakeholder downstream of the recycling chain (US$.kg^{-1}).

Meanwhile, the *Value Appropriation Proportion* (*VAP*) for each stakeholder *i* was calculated by the difference between the price sold and the price bought of the recyclate divided by the final monetary price of the recyclate sold by the reprocessor and bought by the product manufacturer, as in **Eq. (7)**.

$$VAP_i\,(\%) = \frac{a_i - b_i}{a_{final}} * 100 \quad \textbf{Eq. (7)}$$

Where: for each stakeholder *i*, *VAP* is the Value Appropriation Proportion (%); a_i is the price that the stakeholder sold one kg of recyclate to the stakeholder upstream of the recycling chain (US$.kg^{-1}); b_i is the price that the same stakeholder bought one kg of the same recyclate from the stakeholder downstream of the recycling chain (US$.kg^{-1}); and a_{final} is the final monetary price of the recyclate sold by the reprocessor and bought by the product manufacturer (US$.kg^{-1}), which in our case study for HDPE, is US$ 1.23 kg^{-1}.

Results and Discussion

4.1 Rigid HDPE recycling chain: nodes and stakeholders

The HDPE packaging recycling chain starting in Cachoeira de Minas, from waste generation to the production of secondary materials, can be analysed as a technical network (Fig. 1**)**, where stakeholder relationships, nodes, and flows are illustrated. A description of each of these elements in the technical network is given in this section.

From Fig. 1, the *production node* includes the production and retailing of a diversity of product items made of HDPE plastic, most of them using HDPE for packaging. *Waste generation node* shows where HDPE waste is generated by the population of Cachoeira de Minas. The *waste disposal node* represents waste that is collected and disposed of in a sanitary landfill. Finally, the *processing nodes* include four subnodes: 1) *recovery subnode*, with selective (i.e., separate) collection of HDPE together with other recyclables such as paper, cardboard, glass, metals, and other plastics (then, materials are sorted out and baled separately); 2) *trading subnode*, where resorting of materials takes place if needed, in addition to accumulation and storage, and trading HDPE in considerable quantities; 3) *reprocessing subnode*, cutting, cleaning, and converting HDPE into secondary commodities; 4) *transformation subnode*, with the manufacturing of new components and products incorporating recycled HDPE (r-HDPE).

Table 1 presents all the stakeholders identified in the rigid HDPE packaging recycling chain, starting in Cachoeira de Minas and Table 2 presents a comparative characterization of the direct stakeholders (those who are handling the HDPE waste) in technical, economic, social, and environmental dimensions. Figure 2 presents the processes of ACLAMA, which is the most important organisation here, performing the collection and sorting of recyclables (Fig. 2A), and Reprocessor B, which reprocesses HDPE packaging into pellets (Fig. 2B).

Table 1
– Stakeholders identified in the recyclable HDPE chain starting in Cachoeira de Minas, Brazil.

Type	Stakeholder	Stakeholder abbreviation	Role	Node equivalence
Direct – handling plastic recyclate	Households and small commercial enterprises	GEN	Waste generation	Waste generation node (WG)
	ACLAMA (Waste Pickers Association)	CSC	Collection and sorting	Recovery subnode (REC)
	Company A[a],	LSD	Large scrap dealer	Trading subnode (TRA)
	Companies B[a], and C[a],	REP	Reprocessors	Reprocessing subnode (REP)
	Company D[a],	MAN	Manufacturer	Transformation subnode (MAN)
Indirect – not handling plastic recyclate	Cachoeira de Minas local authority	PUB	Public manager	-
	Sanitary Landfill operator	SL	Land disposal of waste	-
	NGO	NGO	Technical consultant	-
	Various companies	IND	Consumer goods sector	-

[a] For anonymity, private sector stakeholders were identified as companies A, B, C, D.

Table 2

– Comparative characterization of the direct stakeholders in the recyclable HDPE chain starting in Cachoeira de Minas, Brazil in technical, economic, social, and environmental dimensions.

Technical dimension				
Stakeholder/ Aspect	**ACLAMA (Waste Pickers Association) (CSC)**	**Company A (LSD)**	**Companies B and C (REP)**	**Company D (MAN)**
Primary role	Sort recyclable waste materials (incl. baling and storing), and they trade - sell to large scrap dealer	Store and trade recyclable waste materials in big quantities – they buy from Collectors and Small scrap dealers, and sell them to Reprocessors	Convert materials into secondary commodities and trade them – they buy from Sorting centres/Scrap dealers, and sell them to Manufacturers	The end users of secondary materials in the production of new components and products – they buy from Brokers and Reprocessors
Secondary role	Door-to-door collection	Sorting and semi-reprocessing (e.g., removal of impurities, cleaning, cutting, crushing); logistics	Logistics	Not applicable
Recyclable material handling	ACLAMA collected 439 Mg of potential recyclables in 2016 (Sakamoto et al., 2021), equivalent to 24% of municipal waste generated in Cachoeira de Minas. Sort all recyclables in 34 categories, including 14 types of plastics (22%), 8 kinds of paper or cardboard (51%), 7 types of metals (9%), 3 types of electronics (0.2%), 1 glass type (2.4%),	They work with all materials sometimes re-sorting to improve quality. Then, accumulate materials in greater quantities to sell to Reprocessors. They work with 20 types of polymers, and 2 kinds of HDPE: coloured and white. The company reported to sell HDPE to 5 different Reprocessors and location but did not disclose which companies exactly.	Both companies had experiences with other types of plastics such as polypropylene and PET but were not successful. They decided to work fully with rigid blow-moulded HDPE, either natural (transparent), white, coloured, or black. HDPE bales come from 4 to 5 suppliers, such as organisations of waste pickers, waste companies and scrap dealers. HDPE can be:	It reported to produce 1 billion packaging units per year using 12,000 Mg of recycled resins per year. Final products include packaging for hygiene products or food products sold to multinational consumer industries. It works with HDPE, PP, LDPE, PET, PVC, and other types of polymers.

Technical dimension				
Stakeholder/ Aspect	**ACLAMA (Waste Pickers Association) (CSC)**	**Company A (LSD)**	**Companies B and C (REP)**	**Company D (MAN)**
	other types of waste (3.5%).			
Technology	Conveyor belt for sorting; Vertical pressing machine	Conveyor belt for sorting; Vertical pressing machine; Fork-lifts	Conveyor belt for sorting with automatic magnet segregators; Shredding machine; Decantation tank; extrusion machine; pelletizer machine; Fork-lifts	Extrusion blow moulding machine; 3D printers
Personal Protective Equipment (PPE) use	All PPE is donated, and some pickers do not wear them because they do not have funds dedicated to this purpose and perceive gloves as slowing the sorting down (Oliveira, 2018).	Mandatory use of PPE.	Mandatory use of PPE.	Mandatory use of PPE.
Reject waste (non-recyclable)	Some collected materials (rubber, hoses, non-recyclable plastics, and cloths) do not have a market in the region, forcing ACLAMA to consider them as rejects – about 11% of all received waste. Municipality pays for it for reject collection.	-	They reported a 20 to 25% loss rate, because of dirt, humidity, other plastics that not HDPE blow-moulded type, metals, paper, and cardboard.	It does not have a significant reject rate (lower than 0.01%).

Technical dimension				
Stakeholder/ Aspect	**ACLAMA (Waste Pickers Association) (CSC)**	**Company A (LSD)**	**Companies B and C (REP)**	**Company D (MAN)**
Contextual information	ACLAMA does not store bailed materials for a long time. They usually sell all materials to a Large Scrap Dealer once a month.	Located 160 km from ACLAMA. One truck load of HDPE is usually 10 Mg. One cooperative will only store 0.7 $Mg.month^{-1}$, which would make it necessary for them to accumulate HDPE for 10 months before selling; hence, the role of a large scrap dealer to buy from several cooperatives and small scrap dealers to accumulate and meet the recycling industry's requirements for materials.	Usually, REPs pick up the loads, but some suppliers might bring it to REP. The cost to pick up a 7-tonne load is R$ 0.07.kg^{-1} (US$ 0.02.kg^{-1}). Suppliers must have a full load before selling. When secondary commodities are ready, they are sold to 4 to 5 different buyers (manufacturers). Transport is done either by the reprocessor himself, or clients come to pick up with their own truck or hire a third to perform this service.	It has ISO 9000 since 1997, it was the first packaging producer to use recycled resins since 2003 and the first national company to perform Bottle-to-Bottle recycling for PET since 2007. Its process for HDPE packaging production is using the Extrusion Blow Moulding process, with automated technology and highly controlled environment, to produce different sizes packaging from 3 to 30 litters. The company also has a laboratory to test new products and 3D printers.
Rigid blow-moulded HDPE input ($kg.y^{-1}$)	5,750	5,180	5,126	Recycled: 4,101
Material output ($kg.y^{-1}$)	5,180	5,126	4,101	-
Material reject proportion wt. (ar)	11%	1%	20–25%	0.01%
Rigid HDPE processing capacity ($Mg.y^{-1}$)	6	360	3,600–18,000	12,000

Technical dimension				
Stakeholder/ Aspect	**ACLAMA (Waste Pickers Association) (CSC)**	**Company A (LSD)**	**Companies B and C (REP)**	**Company D (MAN)**
Economic dimension [a]				
Rigid HDPE buying prices (US$.kg^{-1})	Obtained for free from waste generators	White: 0.41 Coloured: 0.35	White: 0.45 Coloured: 0.37 Black: 0.31	White: 1.39 Coloured: 1.15 Black: 1.05
Operational and maintenance costs (US$.kg^{-1})[b]	0.01	0.05	N.A.	N.A.
Capital cost (US$)[b]	21,818.42	N.A.	N.A.	N.A.
Rigid HDPE Sale prices (US$.kg^{-1})	White: 0.41 Coloured: 0.35	White: 0.48 Coloured: 0.43	White: 1.39 Coloured: 1.15 Black: 1.05	N.A.
Rigid HDPE Revenue/Profits (US$.kg^{-1})	US$ 0.37	US$ 0.08	White: 0.94 Coloured: 0.78 Black: 0.73	N.A.
Social dimension				
Number of jobs	13	22	13–98	1,100
Gender ratio (M:F)	9:4	N.A.	12:1	N.A.
Working hourly wage (%)	36%	N.A.	N.A.	N.A.
Type of work	Employees are associates	CLT (Consolidated Labour Laws) system	CLT (Consolidated Labour Laws) system	CLT (Consolidated Labour Laws) system
Use of PPE	Sometimes	Yes	Yes	Yes
Child labour	No	No	No	No
Environmental dimension				
Energy consumption	Low	Medium	High	High

Technical dimension				
Stakeholder/ Aspect	**ACLAMA (Waste Pickers Association) (CSC)**	**Company A (LSD)**	**Companies B and C (REP)**	**Company D (MAN)**
Environmental Impact Assessment (permit)	No	Yes	Yes	Yes
Water quality control [c]	Not applicable	Not applicable	Yes	Yes
Air pollution control [d]	Not applicable	Not applicable	Not applicable	Yes

N.A.: Not available.

[a] Currency equivalence conversion applied: US$ 1 = R$ 3.816 (2019)

[b] For all materials not only HDPE

[c] If the water used is treated in the same facility according to the local environmental body's standards.

[d] If gas emissions output flow (i.e., process air) is generated, it is treated using air pollution control equipment such as filters, according to the environmental body's standards.

This case vividly demonstrates that even when dealing with just one recyclable material (rigid HDPE), multiple stakeholders are involved in the recycling chain, in line with previously reported evidence (Rutkowski and Rutkowski, 2017). Even though the original quantity of rigid HDPE waste generated can be considered small (estimated at 10 $Mg.y^{-1}$ of HDPE rigid packaging at the City of Cachoeira de Minas), the diversity of roles of stakeholders adds complexity to these systems, presenting challenges for policy-making/ interventions. For example, ACLAMA is sorting into 34 categories of recyclable material outputs. When assuming that each of them has its own recycling chain, the traceability of material flows and allocation of origin become complicated tasks – a main desirable element of a genuine circular economy as currently debated (Rumetshofer and Fischer, 2023; Shamsuyeva and Endres, 2021). Evidently, even for such a comparatively simple, i.e., narrowly defined in scope and origin system in Brazil, these challenges are present.

Figure 3A maps the nodes identified for the HDPE recycling chain starting in Cachoeira de Minas, to offer a visual appreciation of the transportation distances involved. **Figure 3B** presents the material flows for the case study in an MFA form. There are several categories of HDPE materials that are sorted in the generated waste, such as form (blow-moulded rigid, injection rigid, films) and colour (coloured, white, natural, black). The diagram concerns HDPE packaging waste, focusing on blow-moulded rigid packaging, for example, shampoo bottles and cleaning supplies packaging, coloured as well as white and black.

Although nodes start in the city of Cachoeira de Minas with the waste generation node, recyclable HDPE waste travels up to a radius of 400 km to subsequent nodes in the chain. Starting in Cachoeira de Minas in the state of Minas Gerais, it travels North for 150 km to the LSD (trading node); then it goes either 400 km East or 250 km South to the several possible *reprocessors*, finally ending in the *manufacturers* located at least 40 km from the reprocessors and 200 km from Cachoeira de Minas. For reference, the direct distance between London and Leeds is 320 km, in the UK, which gives a perspective of how much waste travels in Brazil, increasing transportation impacts. The map also demonstrates that recycling chains of recyclable materials might cross the borders of municipalities and states in Brazil, traveling by road; pointing out the importance of optimizing the logistics to provide viability for the recycling industry. Furthermore, in Brazil reprocessing (REP) and manufacturing (MAN) of HDPE takes place mostly in the state of Sao Paulo, probably because this state is the most industrially developed in the whole country with most of the recycling industries located there (Astolpho et al., 2020).

Most interestingly, despite r-HDPE being a commodity widely subject to transboundary trading (i.e., across national borders) (Bishop et al., 2020), reprocessors interviewed here (Section 3.2) mentioned that all HDPE is mechanically recycled within the borders of Brazil. Such statements are in line with the fate reported by Pimentel Pincelli et al. (2021) and Rukowski and Rutkowski (2017), indicating that the current local sources of material cannot meet the demand and that it is of sufficiently suitable quality for the Brazilian manufacturing needs.

An overall MRRP of ca. 38% wt. (ar) is accomplished in this system, measured as the percentage of mass of rigid r-HDPE entering manufacturing over the mass of rigid HDPE waste generated (Fig. 3B). This MRRP is exemplified and scrutinised stage by stage in each stage of the supply chain below.

4.2 Recycling chain – physical processing - rejects

ACLAMA (a waste pickers association in Cachoeira de Minas – the single *collector and sorter* here – CSC) is currently collecting 53% wt. (as received – ar, i.e., on a wet reporting basis) of all HDPE waste generated by households and small commercial establishments of Cachoeira de Minas – the residual 37% wt. (ar) is disposed of at the local landfill, designated with local terms as ‘sanitary’, i.e., engineered to a basic degree. The ‘rigid HDPE’ is one of the 14 categories of plastics and one of the overall 34 output categories of all types of recyclables the association sorts out of MSW (Table 2) (Sakamoto et al., 2021).

Sembiring and Nitivattananon (2010) characterised the informal recycling chain in Bandung, Indonesia, estimating that 2,915 people were part of the IRS collecting 350 Mg per day of recyclable materials. For plastics, the IRS only collected 8%, while in Dhanbad, India, Kumar et al. (2018) found that 43% of plastics were collected for recycling by the informal sector.

During the sorting process of all the materials collected by ACLAMA (CSC), a material reject proportion (MRP_{CSC}) of 11% wt. (ar) are sent to the landfill as rejects, due to liquids in bottles, impurities (food or other non-recyclable materials such as lids, stickers, and labels), and both targeted and non-targeted for recycling items constituting smaller-size pieces, too difficult to manually sort. Here, we assumed that this average material reject rate (i.e., 11% wt.) applies to the rigid HDPE category since performing a detailed waste audit was not within the scope of this research. Subsequently, ACLAMA would sell around 89% wt. (ar) of the rigid HDPE recyclables to *large scrap dealers* (LSD) – $MRRP_{CSC}$. We scrutinise this result and underlying assumptions onwards.

This could be considered as a low material reject proportion (MRP) when compared to the performance of other waste picker organizations in Brazil: an average of 20.2% wt. (ar) MRP was reported for 16 organizations in the State of Espírito Santo in Brazil (Meira de Sousa Dutra et al., 2018). One could argue that a MRP of 11% wt. (ar) is reasonable for a sorting operation that: (1) features as many as 34 outputs (multiple recyclate type outputs minimize the number of non-targeted for recycling materials); (2) they are sorting source-separated material; and, (3) the quality of which is checked on the very spot of collection by the collectors themselves, who as experts can identity any non-targeted materials and in the long run educate the waste generators on the items targeted for recycling, via direct in-person interaction. Indeed, this recyclables' collection modality has been speculated to result in overall lower rejection rates as part of a recycling system, in comparison with formal industry systems both co-mingled and curbside (but less so) (Lau et al., 2020). That difference could be result from the collection processes: if the selection of recyclables is made by the waste generators alone, typically householders, who as non-experts are not able to sufficiently distinguish the targeted from the non-targeted materials and/or the contraries, they could be increasingly misplacing for recycling items that would have to be rejected onwards.

In contrast, the next step in the chain, the *large scrap dealer* (LSD), stated a mere 1% wt. (ar) MRP_{LSD} for their process, therefore a 99% wt. (ar) $MRRP_{LSD}$. According to them, these minimal material losses are due to liquid (water) and other small impurities; and the percentage is that low because they carefully select the materials they buy. For this reject rate to be correct, either the material sorting at the previous supply chain stage (the ACLAMA and equivalents) should have produced a very pure output meeting the exact specifications of the LSD, or LSD could have a way to disperse/ conceal any potential rejects in the material they sell to the next node or the buying specifications of the reprocessors would be the same as of LSD, which does not hold.

At the next node, *reprocessors* (REPs) target a specific sub-fraction of rigid HDPE waste: blow-moulded and as low material contamination as possible; as a result, they experience the lowest $MRRP_{REP}$ – 80% wt. (ar) – and the highest MRP_{REP} in the chain – 20% wt. (ar). They allocate this to impurities such as dirt and humidity, along with other non-targeted recyclable materials such as injection-moulded HDPE, metals, paper, and cardboard that are allegedly often found in the middle of bales bought from their suppliers (a deceit strategy called bale 'beautification').

Thus, the material reject rate reported in the LSD node of the chain might not always reflect a high-purity output sold to REPs. REPs reported that before buying from suppliers, they apply an approximate two-stage quality assurance (QA). For example, initially (QA part 1), they would remotely examine and assess images of the baled materials on offer: if the quality of the bales is not good enough, they would save on logistics, not collecting the shipments. Subsequently (QA part 2), REPs also usually employ an expert who will perform a visual assessment on the transaction site: If they do eventually identify a load of low quality (high potential rejects), they will lower the price on the spot. They reported that the impurity that mostly lowers the price of a shipment is the presence of black HDPE bottles in the middle of other colours, other than black as being deemed as more valuable. Depending on demands, pelleted r-HDPE can have different degrees of quality (grades). For example, if lids and labels made of polypropylene are also processed, the end pellets have a ca. 10% wt. contamination and, therefore, lower prices. For the buyer (REPs), the purer the HDPE the better, because contamination with other plastics might affect the extrusion machinery and temperature needed for the reprocessing. According to REPs, even with attempting to enforce a strict quality control for their suppliers, involving pictures and visual auditing of bales when trucks are received on their premises, the process still results in non-negligible losses (on a mass basis).

REPs have no option but to be strict on their output material purity because their product (blow-moulded r-HDPE resin pellet) competes with virgin resin. Therefore, their high reject rates can be explained by a strict and possibly steep differentiation between the qualities of feedstock supplied to them and the output demanded from them. Whereas they ultimately depend on purchasing from LSDs, apparently, they cannot effectively control the quality, forced to account for potential financial losses due to the high MRP from sub-standard quality feedstock by adapting the purchasing prices they offer. This indicates what we could call an 'informality transition threshold', at least from a material quality point-of-view: their input interfaces with loose standards and procedures ingrained in an informal and therefore loosely defined system, whilst their outputs must be supplied into a formal strictly prescribed industrial process of mass consumer product manufacturing.

The MRP_{MAN} in the transformation stage (MAN) is reported as negligible at 0.01% wt. (ar), according to *manufacturers*, therefore an $MRRP_{MAN}$ of 99.9% wt. (ar) To produce packaging mainly virgin resin is mostly adopted and the rate at which r-HDPE is added with recycled content is variable. The use of virgin resin was stated as wide as in the 10–90% wt. range. For comparison, for PET, 35% wt. of recycled resin is estimated to be used with 65% wt. of virgin resin (Chaudhari et al., 2021), although 100% r-PET bottles are already being used in the beverage sector by now (Nestlé Egypt, 2020).

The overall MRP, calculated by **Eq. (5)**, was 28.7% wt. (ar), which could be considered high; for example, compared to another study that found a maximum MRP of 10% wt. (ar) (Jaligot et al., 2016); but it shows that the HDPE recycling industry could improve the recovery for recycling, as in the case of Cachoeira de Minas, Brazil; and it is even more important as this is a result of collection by organised (formalised) informal waste workers (waste pickers and sorters, IRS). It is definitely, much higher than the 8.2% wt. (ar) overall global and all-plastics MRP (or 'recycling rate', obtained as 'secondary plastics' divided by ‘plastics waste’ for the reference year 2019) estimated by the most recent authoritative model available, the Global Plastics Outlook, released in 2022 by OECD (OECD, 2022).

4.3 Rigid HDPE recycling chain – monetary and information flows

The monetary flows identified are presented in Fig. 4A while the information flows are presented in Fig. 4B. Concerning monetary flows (Fig. 4A), Cachoeira de Minas municipality pays for part of ACLAMA’s operational expenses (OPEX): land/building rent, water, and energy utility bills, the recyclables collection driver, and the gate fee for disposing off the residual waste (rejects) to the landfill, resulting in a total cost of US$ 15,299 in 2019 (US$ 1 = R$ 3.816–2019). Besides, they also donated (capital expenses – CAPEX) a press machine (US$ 7,714). On the legal arrangements, ACLAMA do not have a service contract with the municipality this is in contrast to what other service providers have - for example, waste collection companies and/or sanitary landfill operators, but the local law No. 2,496/2017 (Câmara Municipal de Cachoeira de Minas, 2017) authorizes the city to pay for these expenses. In a previous study providing a financial diagnosis of the ACLAMA cooperative (Sakamoto et al., 2021), we estimated the operational cost for the sorting at US$ 47 per tonne (Mg) – to put this in perspective, the municipality pays landfill disposal gate fee of US$ 74.3 per Mg.

Even with these CAPEX and OPEX investments from the municipality, there are processing capacity limitations at this beginning of the recycling chain. In a main bottleneck, ACLAMA are not able to accumulate substantial quantity (bales) of HDPE, because: 1) they do not have fork-lift equipment to pile bales; 2) it would probably take around 10 months of accumulation to close a full truckload; 3) cash flow difficulty: waste pickers claim that storage would not be feasible in terms of financial management, because they need to be selling that material right away, and practically urge to be paid fast, while reprocessors might take up to 6 months to pay.

Another information flow identified is that of a consulting firm hired by one company (from the consumer goods industry) to advise ACLAMA and other waste picker organisations in the region for US$ 4,700 per year. They are part of a program that invests in reverse logistics of the plastics packaging of this company. Many similar firms are hired by the private sector in Brazil to attempt incremental improvements for waste picker organisations (Reciclar pelo Brazil, 2021).

In the recycling chain, the value creation and appropriation accomplished without taking any costs into account is as follows: the collection and sorting cooperative ACLAMA (CSC), formerly IRS, has the opportunity to obtain the potentially recyclable HDPE for free from the waste generators (households and enterprises). This collection costs the generators US$ 0.05 kg^{-1} (US$ 47.00 Mg^{-1}) via taxes from the municipality. ACLAMA sells to the next value chain node, the large scarp dealer (LSD), at US$ 0.38 kg^{-1} (US$ 380.00 Mg^{-1}). Opposite of what we found in our study, the Dhanbad, India waste pickers (Kumar et al., 2018) sold HDPE at a higher price than other stakeholders (US$ 0.08.kg^{-1}, compared to US$ 0.04.kg^{-1} for itinerant waste buyers and US$ 0.03.kg^{-1} for scrap dealers). This could be because

HDPE and PET are more valuable than other materials, yielding more revenue than other materials, such as glass and low-value plastic films.

While there is not a scientifically single defensible way to quantify a percentage of the value per mass unit created by ACLAMA – Value Appropriation –, we have estimated a worst case by assuming a price of near zero value (i.e., US$ 0.01 kg^{-1}) using **Eq. (6)** (for an empty rigid HPDE bottle in a take-back scheme in a Latin America and Caribbean context). The value appropriation for ACLAMA (VA_{CSC}) would then be 3,700%, making the IRS a major value creator and possibly appropriator.

The onward chain step presented a value appropriation at 21% of the input cost price (from US$ 0.38 kg^{-1} input to LSD to US$ 0.46 kg^{-1} input to REPs) (VA_{LSD}); and the subsequent at 167% (from US$ 0.46 kg^{-1} input to REPs to US$ 1.23 kg^{-1} input to manufacturers – approximately, as it refers to a mixed HDPE grade average) (VA_{REP}). Therefore, we document a most substantial value creation and appropriation by the initial collection and sorting formalised former IRS stage (CSC); followed by substantial value appropriation by the final stage of production of r-HDPE pellet (REPs). Whereas value appropriation at the material level does not coincide with value appropriation by the organizations or the individuals employed in them (and it does not incorporate material losses and wider costs and scale of activity/production), it demonstrates a fundamental starting point on the value to be distributed.

Another way to consider it is using the value appropriation proportion (VAP) – from **Eq. (7)** – where approximately for a mix of grades, from 100% of the blow-moulded rigid r-HDPE price (US$ 1.23 kg^{-1}), VAP_{CSC} is ca 30.1% of the value appropriation per mass unit– i.e., the IRS, VAP_{LSD} is 6.5%, and VAP_{REP} is 62.5%. As a summary, the MRRP, MRP and VAP of each stakeholder in the recycling chain were calculated using **Equations (2)**, **(4)**, and **(7) respectively** and can be seen in Fig. 5.

The economic viability of producing recycled resins remains a core debate since their prices have been historically volatile and highly dependent on virgin resin market pricing (Getor et al., 2020). Reprocessors buy HDPE without taxes and sell them paying all taxes (another informality transition threshold within the system under examination), which can partly explain the relatively high sale price (US$ 1.23.kg^{-1}) compared to buying prices (US$ 0.46 kg^{-1}). Without generalising, in the case at hand, virgin HDPE resins could be bought at US$ 1.83.kg^{-1} (US$ 1 = R$ 3.816–2019), being also technically superior for both the manufacturers' machinery performance and regarding end product technical quality (as a material engineered to exact technical specifications - sustainability actual and perceived performance aside). Therefore, the manufacturers claim that r-HDPE resins are sold by reprocessors at US$ 1.23.kg^{-1} (i.e., at ca 30% lower than the virgin resin price) can be deemed as comparatively 'expensive'. So far, consumer goods companies in Brazil do not have any financial incentives from the government for using recycled content in their products – such as, for example, the legally binding policies and fiscal incentives introduced in the European Union (EU) and the UK (Peszko, 2023), where products with recycled content of 35% or higher is tax free – which preserves the price differential with virgin resins the main demand driver for the r-HDPE market.

Given the reported material reject proportions at 11% wt. (ar) for CSC, 1% wt. (ar) for LSD, 20% wt. (ar) for REP, and 0.01% wt. (ar) for MAN (Fig. 5), one could be tempted to conclude that the reprocessors are disproportionately bearing the costs in this specific supply chain. However, they also create a substantial increase in the value of the material (62.5% of value appropriation proportion, yet with taxes included), having had to adjust their purchasing prices to counteract the anticipated monetary losses from rejects. This could be an intriguing result - the literature is full of claims of perceived financial exploitation of the IRS by the aggregators / middlemen (Coletto and Bisschop, 2017; Majale et al., 2016), but research to date has focused less on comparative examination along with reprocessors / other value chain stages.

In Peru, collection centres pay waste pickers US$ $0.30.kg^{-1}$ of HDPE, while selling to reprocessors for US$ $0.33.kg^{-1}$ (Torres and Cornejo, 2016), which means a 10% value appropriation proportion, in comparison to 30.1% found in our case study. In the reprocessing stage, Egypt presented a value appropriation of 47% (Jaligot et al., 2016) while our case presented 62.5%. This could be because costs in this stage might be higher, including the taxes - a speculative explanation.

Concerning information flows (Fig. 4B), they were identified in the waste management system with public managers being the main stakeholders responsible for information concerning solid waste management (Fiore, 2013). In this case study, we identified three characteristic types of information flows coming from different stakeholders: (1) technical consultancy, (2) environmental education, and (3) material quality requirements. The technical consultancy flow (1) includes consulting to empower and strengthen the waste pickers' organisations. Environmental education flow (2) refers to waste pickers' door-to-door waste selective collection, explaining in person to waste generators (e.g., householders) how to correctly segregate their solid waste at source, i.e., at the very point of generation (Section 3.2). The information flow concerning the quality of HDPE demanded by industry (3), starts at *manufacturers* and is disseminated backward through each stage – the effect dissipated the further away we move from this value chain stage, as it is evident by the loose quality perceptions and practice in the *sorters – large scrap dealers* transaction interface.

Information flows are crucial for optimizing recycling value chains and improving circular economy systems. In our case, information flows were all informal and not intentional. Official and documented technical knowledge exchanges were not observed between stakeholders in the value chain – except for technical consulting organisation advice at ACLAMA, but without communication with other stakeholders in the chain. In principle, this shortcoming could provide a solid basis for improvements across the recycling chain; theoretically, stakeholders could be collaborating with each other to accomplish improvements in the overall operational performance (Shamsuyeva and Endres, 2021). Characterizing service flows (i.e., mixed and selective collection of recyclables and transportation of recyclables) were out of scope here, but future analyses could add this aspect to the analysis.

4.5 Limitations

Under this research there was no means of obtaining full and detailed data from some of the stakeholders: for example, MAN and LSD stakeholders did not provide details on labour and wages.

There is no guarantee that the water consumption/ treatment and air pollution control at the reprocessing and transformation stages, respectively (even with environmental permits issued by a local authority or environmental body) have adequate effectiveness to avoid environmental degradation. In this sense, more detailed environmental assessments of each stakeholder are needed to be made publicly available. More transparency from all stakeholders in the recycling chains could benefit not only research work such as this one, but also policy-making. Direct validation of the statements on reject rates was not feasible. Future research could enhance the analysis by: (1) including economic and fiscal incentives scenario studies, in order to optimize the performance of recycling chains, compared to virgin plastic materials; (2) evaluating the technical loss of quality between different stakeholders in recycling chains; and, (3) assessing the impact of other legislation incentives in the recycling chain.

Conclusions and Outlook

The fate of recyclable materials collected for recycling and especially plastics, which are extremely diverse, has been notoriously difficult to establish. The same applies to collection and recycling efforts that involve waste pickers and are based in the Global South. Here, for the first time, we provide a comprehensive baseline study for one type of plastic in one middle-income country, including the characterisation of each stakeholder identified in the recycling chain system in four dimensions: technical, economic, social, and environmental, and the analysis of value creation and appropriation considering the recovery and reject rates. Although similar studies with the same indicators do not exist, we also compared with elements that can be sourced elsewhere.

Novel insights with actionable implications on both research and practice emerge here; but as these are for just one specific case study, it is highly advisable to be treated with caution and to be complimented with equivalent studies in the future. In this Brazilian recycling value chain, notable conclusions are drawn: First the analysis of the rigid HDPE recyclables demonstrated a value chain with discrete roles and clear transition points of informality to formality, and practices: (1) collection and sorting waste pickers' organisations, which turn the 'waste' into a commodity (recyclate) in the first place; (2) large scrap dealers, who mostly stock, aggregate materials at scale; (3) reprocessors, usually specialised in one or two types of plastic polymers, having to operate at increased formality standards, including quality assurance; and (4) product manufacturers, who use the recycled resin in different products – largely a formal sector if consumer mainstream goods are involved.

Second, a relatively simple system and low-tech operational arrangement can collect a substantial amount of waste, with minimal government or other instructive / controlling organisation involvement. Third, the system, despite the very concentrated focal point of collection at the very start can result in substantial complexity regarding geographies and processing stages involved, poses great challenges on material flow traceability and wider transparency. Fourth, it is clearly established that the value creation and appropriation by generating and trading suitable recyclate at each stage is directly and strongly interlinked with the quantities of rejects (losses), allowable and detectable contamination levels, and the monetised value of recyclate. The various stakeholders handling the material along the recycling value chain formulate differentiated strategies and operational approaches so that they can profitably operate. These approaches may directly compete rather than being synergetic, revealing large margins for optimisation, if theoretically the incentives could be aligned. Specifically the information disparity and verification means and opportunities on the quality standards of the recyclate, is resulting in high overall reject solid rates. If the informal waste workers could be trained and more widely enabled to provide more quality assured outputs this could have transformative effect upon the entire value chain. Fifth, given that the waste informal workers obtain the recyclables 'for free', they achieve a high value creation and associated value appropriation – they are privileged in that sense, by being at the very beginning of the value chain. Sixth, ultimately, despite internist limitations, simplicity and failures of the supply chain, including high solid reject rates, it is instrumental that due to the highly effective collection for recycling and copious sorting efforts of the IRS, a comparatively very high actual recycling rate is achieved for rigid HDPE: ca 38% wt. (ar).

Evidencing the intricacies and challenges of a Global South circular economy system, these insights on an HDPE packaging recycling loop demonstrate a highly performing and yet not optimised recycling system. Our evidence, findings and conclusions deepen our understanding of low- and middle-income countries complex reality of plastics recycling chain systems. If plastic pollution is to be eliminated (or at least substantially mitigated) and genuine circularity of resources established within a Just Transition framework, interventions would be needed to adjust the value creation and appropriation. For rigid HDPE we start having a much clearer understanding of the system baseline and its nuances across the recycling value chain in the Global South.

Declarations

Credit Authorship Contribution Statement

Nathalia Silva de Souza Lima Cano: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Visualization; Writing - Original draft preparation and Review & editing. **Emília Wanda Rutkowski:** Conceptualization; Supervision; Validation; Writing - review & editing. **Costas A. Velis:** Conceptualization; Methodology; Supervision; Validation; Writing - Original draft preparation and Review & editing. Funding acquisition.

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Data Availability Statement

All results data are available as part of the article and associated Supplementary Information. Raw data can be available upon request to the corresponding author, with the exclusion of commercially sensitive data, provided to the researchers under a confidentiality agreement.

Ethics statement

All interviewees consented to participate in this research and have it published. The University of Campinas Research Ethics Committee approved the methods (interview and observational) as they comply with international and Brazilian ethical guidelines.

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Figures

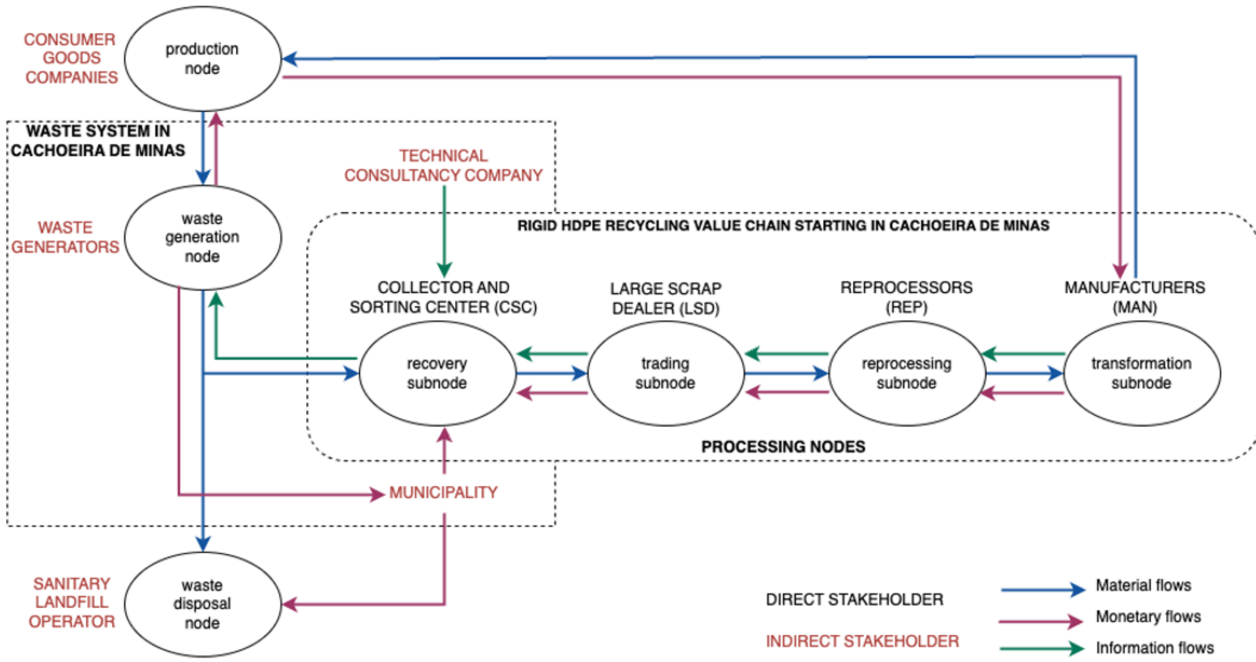

Figure 1

Rigid HDPE packaging recycling chain, starting in Cachoeira de Minas, Brazil. Technical networks are composed of *nodes* and *subnodes* (oval shapes), *stakeholders* (text in capital letters), and *flows* (arrows). Post-consumer waste generation originates from the production node. Waste disposal services are provided by a third party, located in another municipality (60 km away), whereas the recycling chain starts in the municipality of Cachoeira de Minas and expands to other places (administratively). The HDPE recycling chain starting in Cachoeira de Minas goes through four subnodes to reach the mechanical transformation in new products as processed secondary resin, indicating the complexity of the chain under study.

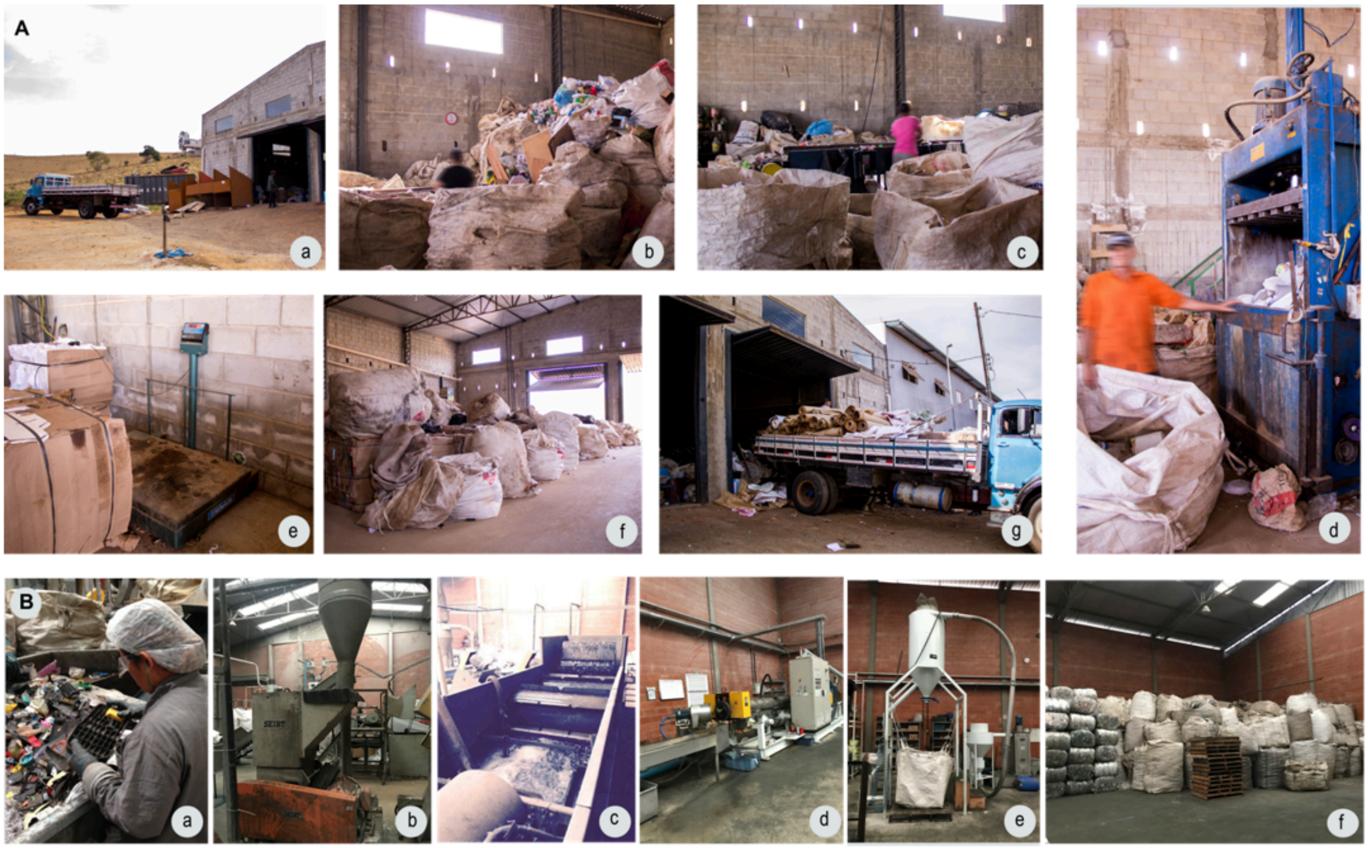

Figure 2

A/B. A: ACLAMA's production process. (a) Material arrival; (b) Initial material storage; (c) Sorting conveyor area; (d) Pressing and baling area; (e) Weighting area; (f) Stocking area; (g) Recyclables commercialization. ACLAMA collects around 500 Mg of potential recyclables per year, from which 5.7 Mg are rigid HDPE packaging. Source: Sakamoto et al. (2021). Reproduced with permission. **B**: Company B's process. (a) Bales are undone and materials are manually sorted in a conveyor belt to clean labels and lids made from different plastic types, occasionally, other materials such as metals, paper, cardboard, and even medical waste are found and sorted out from HDPE; (b) Plastics are shredded in smaller pieces called flakes; (c) Flakes are washed with water only and decanted in a tank; (d) Clean flakes are extruded to strands; and, (e) pelletized (production of pellets); (f) they stored before sales. When secondary commodities are ready, they are sold to four to five different buyers (manufacturers). Source: This study - field visit to company B.

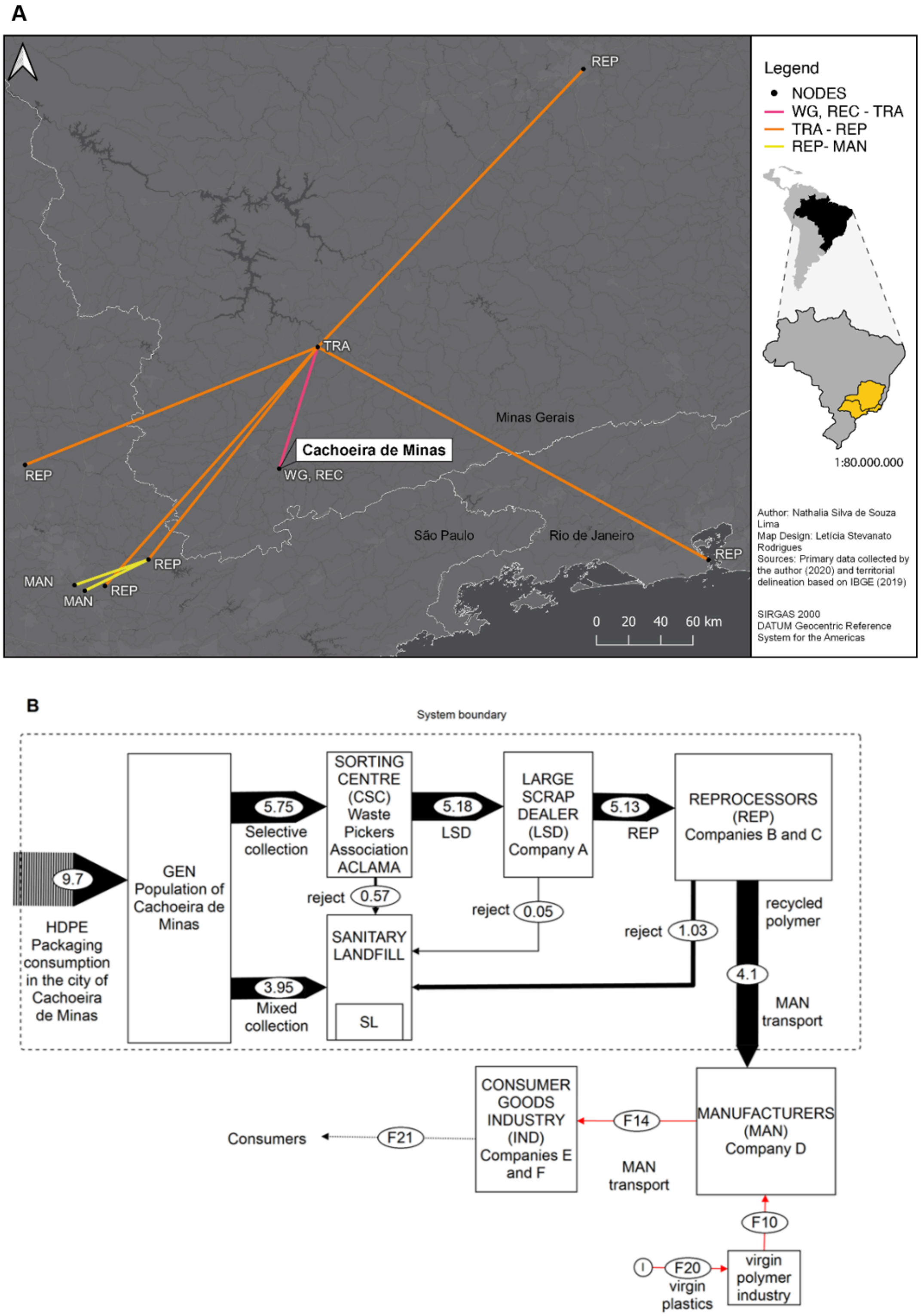

Figure 3

A/B. A: Map of nodes identified in the HDPE recycling chain starting in Cachoeira da Minas. *WG: waste generation node; REC: recovery subnode; TRA: trading subnode; REP: reprocessing subnode; MAN: Transformation subnode*. Sources: Primary data collected by the authors and territorial delineation based on IBGE (2019) IBGE. Software: QGIS 3.12.0. Reference system: SIRGAS 2000 DATUM Geocentric Reference System for the Americas. The HDPE recycling chain starting in Cachoeira is directed to five different reprocessors, despite being a comparatively small quantity. Distances of 40-400 km from nodes are documented. **B:** Material flow (MFA) diagram for HDPE supply chain starting in Cachoeira de Minas, Brazil in the reference year 2019 ($Mg.y^{-1}$). Waste generators (GEN); Sorting centre (ACLAMA – waste pickers association); Large scrap dealer (LSD); Reprocessors (REP); Manufacturer (MAN); Consumer goods industry (IND). Black flows represent collected data from stakeholders; red flows: data not available. Surprisingly for HDPE, 53% of the mass is collected separately in the selective collection stream, and only 37% goes to the landfill, which does not happen in most of the Brazilian cities, where selective collection has a material recovery for recycling proportion (MRRP) of around 5% for most recyclable materials (Abrelpe, 2017). Around 38% wt. (ar) of overall MRRP is achieved here, measured at the input to manufacturing processes, while the overall reject proportion (MRP) was 28.7% wt. ar,

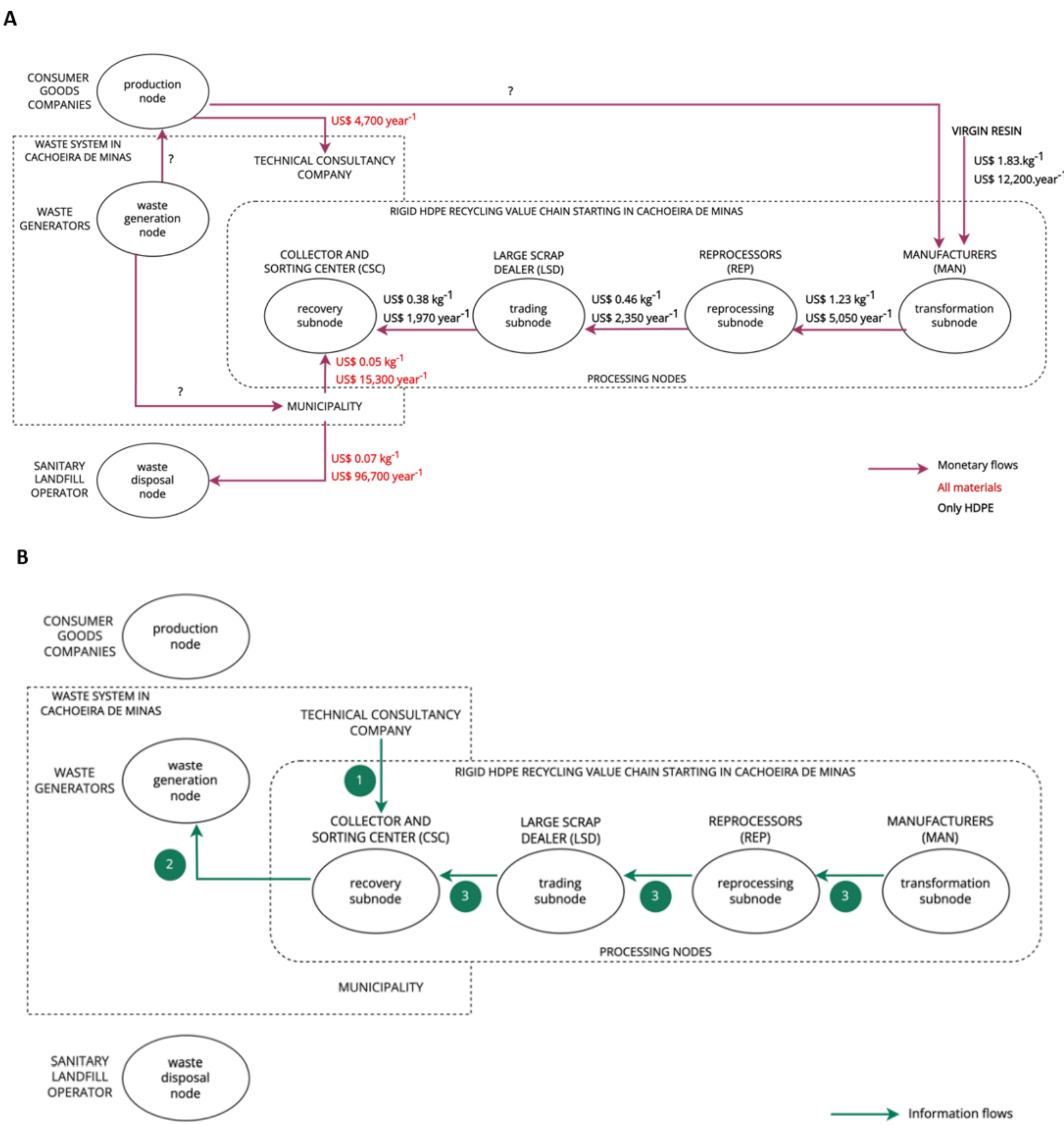

Figure 4

A/B. A: *Monetary flows* for the HDPE recycling chain starting in Cachoeira de Minas. (Currency conversion exchange: US$ 1 = R$ 3.816 (2019)). The question mark (?) symbol represents flows that were not quantified. **B:** *Information flows* for HDPE packaging recycling chain starting in Cachoeira de Minas. The technical consultancy flow (1) includes consulting to empower and strengthen the waste pickers' organisations. Environmental education flow (2) refers to when waste pickers perform the waste selective collection door-to-door, they go about explaining how people should segregate their waste. The information flow concerning the quality of HDPE demanded by the industry (3), starts with Manufacturers, going backward through each stage.

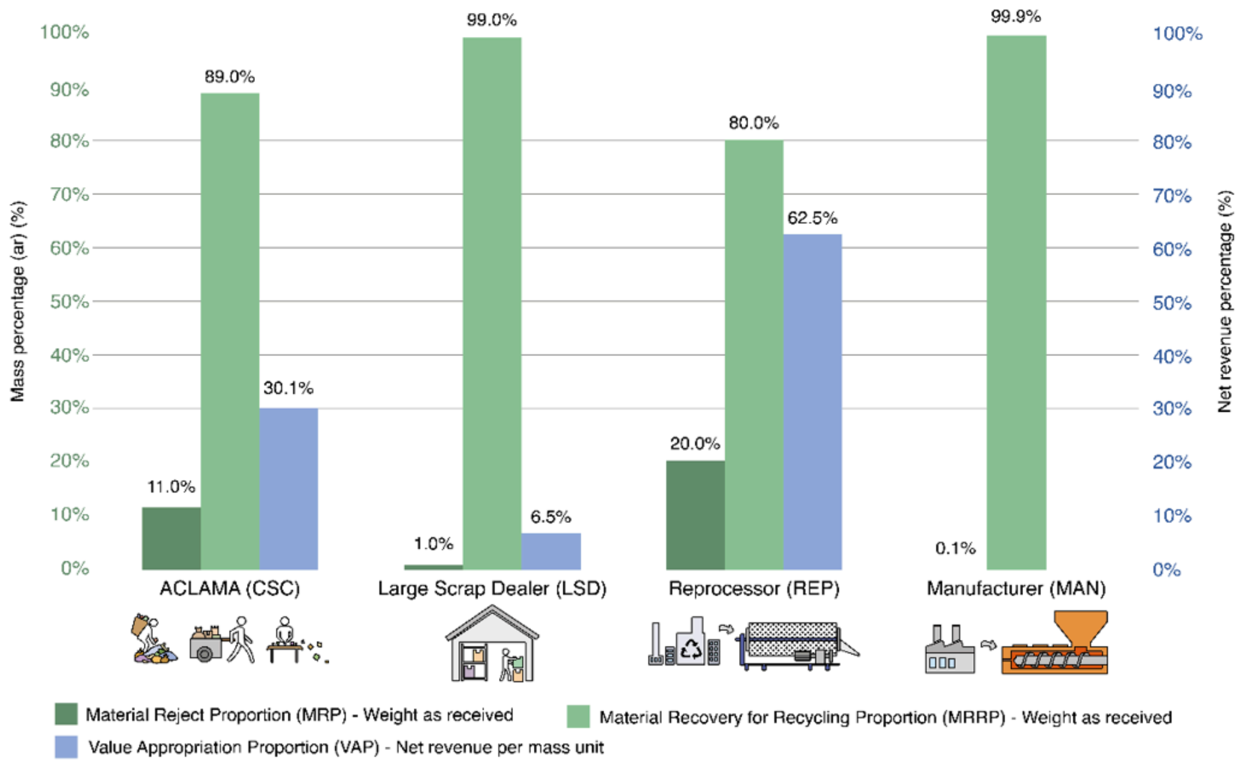

Figure 5

Material Recovery for Recycling Proportion (MRRP), Material Reject Proportion (MRP) and Value Appropriation Proportion (VAP) in each stakeholder of the HDPE recycling chain starting in Cachoeira de Minas. ACLAMA (collector and sorter: waste picker cooperative) and reprocessor (REP) report the highest reject rates, because they have to ensure a high-quality output (input to manufacturers of r-HDPE). HDPE: high-density polyethylene. MRRP, MRP and VAP of each stakeholder in the recycling chain were calculated using Equations (2), (43), and (74) respectively.

Supplementary Files

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