Challenges to reducing post-consumer plastic rejects from the MSW selective collection at two MRFs in São Paulo city, Brazil

Carlos Alberto Correa1 · Marcio Adilson De Oliveira2 · Christiane Jacinto2 · Giuliana Mondelli2

Received: 3 November 2021 / Accepted: 2 March 2022 / Published online: 18 March 2022 © Springer Japan KK, part of Springer Nature 2022

Abstract
The present study is concerned with an overview of the main aspects of the selective collection from the municipal solid waste in São Paulo City and the limitations of its two automated Material Recovery Facilities (MRFs) to tackle the problem of reducing recyclable plastic waste sent to landfills as rejects. The research aimed to characterize the composition of screened mass flows of as-received mixes from the selective collection at the two MRFs through in situ random collection campaigns. The results of the gravimetric analysis have shown that both MRFs provided higher recovery yields (> 40%) for paper, cardboard, Tetrapack®, ferrous and non-ferrous metals (aluminium), akin to some post-consumer plastics (PET, HDPE/LDPE and PP) that ranged from 38% for PP up to 89% for HDPE. Losses in recovery yields of recyclable plastics after the screening process resulted from lack of clear resin label identification, inefficient materials sortation by households and poor recognition capabilities of the MRFs screening devices to target and segregate specific types of plastics such as PS and vinylic. Packaging design complexity, multi-layered material diversity, and food contaminated post-consumer packaging pose further challenges to improve the plastics recovery capabilities of the two MRFs.

Keywords Municipal solid waste (MSW) · Material recovery facility (MRF) · Post-consumer plastics (PCPs) · Selective collection · MSW gravimetry

Introduction
The global capacity of plastics production has been growing exponentially since the 50’s and reached 368 million metric tons in 2019, followed by 367 million metric tons in 2020 [1]. A total amount of 8.3 billion tons of plastics were produced between 1950 and 2015 [2]. Plastics global production itself represents 6% of the oil consumption or about 6% of the oil consumption by the aviation sector. At current growth rates, the plastic sector will represent 20% of the global oil consumption and 15% of the CO2 emissions in 2050. In 2005, a total of 6.3 billion tons of solid plastic waste was generated, with 79% landfilled or discarded in the environment, 12% incinerated and only 9% was recycled. At the present pace, a global capacity of 1 million metric tons per year might be reached within the next decades with unpredictable environmental impacts if rates of recovery and recycling of waste and discard remain at present levels.

The Ellen MacArthur Foundation estimates that 78 million tons of plastics are produced annually from virgin feedstock for packaging applications [3, 4]. Only 14% of this amount is collect for recycling, with 10% recycled into lower value products (cascaded recycling), 4% process losses and only 2% reprocessed as Post-Consumer Resins (PCR). The larger volume of plastic packaging waste is destined to landfills (40%), incineration and/or energy recovery (14%) and leaked into the environment as litter (32%). The growing impact of plastic waste on Municipal Solid Waste (MSW) streams has also been highlighted by Tsiamis et al. [5], whilst The United Nations has declared waste management policies as a top priority to curb plastic littering spread around the world [6].

Reuse and recycling represent the only alternative to divert plastic waste from landfilling, incineration or littering. In terms of waste management, recycling provides the technical means to return raw materials to market by screening and sorting reusable products from the bulk of the MSW.
different classes of plastics which make them hard to be recycled. In particular, those related to PCPs are very hard to be recycled, regardless the huge volume of waste they generate. All these shortcomings hampering mechanical recycling have raised interest over new platforms such as waste-to-energy and chemical recycling to reduce plastic waste. In such cases, the plastic material is modified chemically to break down its molecular structure into its original building blocks that could be used in the production of fuels or monomers as raw materials for new products.

As a consequence of the complexities of PCP recycling, the global amount of plastics ending in landfills by 2015 was nearly half of the produced amount, or about 150 million tons annually, not to mention the amounts that escape the MSW collection schemes and are leaked into the environment. In Brazil, wide availability of virgin resins at low prices, lack of tax incentives for recyclers, contaminated waste streams and a waste collection system strongly focused in the final disposal in landfills, make the plastic recycling sector low competitive, adding to the very low recycling rates of PCRs, as shown in [11].

A big challenge is being posed over Materials Recovery Facilities (MRFs) worldwide in regard to the characterization of the post-consumer waste in terms of its diverse typology. To improve the yield performance and reduce the amount of rejects at MRFs, primary data about the composition of the MSW selective collection are essential to achieve recycling goals. In particular, those related to PCPs whose recycling rates are still rather low due to the material’s inherent complexity and cross-contamination within different classes of plastics which make them hard to be identified and segregated. Recent studies on primary data collected from plants sorting and recycling PCPs in the EU have shown that significant losses of target materials such as PP and PS are more likely to occur both at sorting and recycling stages [12].

Further advances in automated sorting and recycling of source separated MSW has been reviewed in [13] and a comprehensive review of technological state-of-the-art, cases, practice and implications of automated sortation for materials recycling in MSW processing plans was presented by Cimpan et al. [14]. In most MRFs, materials recovery yields rely on optical methods such as light spectrophotometry, designed to read the wavelengths which are associated to a specific color reflected by the surface of the material. In addition to color wavelength recognition, near infrared sensors are capable to differentiate materials density allowing for the processing of different categories of plastics as well as different colors of glass. These sensors are synchronized with air blowers which are triggered to remove the items from the conveyor belt to a single streaming towards the collection bales. Combining several different types of optical sorters with air blowers operating over high speed conveyors allows for both increases in productivity, recalling speed, efficiency, and flexibility of the facility [15].

The amount of mainstream recyclable materials from selective collection in Brazil has been growing steadily in the past 5 years with aluminum and fiber (paper and cardboard) in the leading ranks of the most pursued recyclable waste. The amount of Post-Consumer Plastic (PCP) waste generated in 2018 in Brazil was estimated in 3.4 million tons with only 757 thousand tons (22.3%) mechanically recycled [16]. Apart from PET and HDPE bottles, plastics are still lacking behind aluminum and paperboard in recycling recovery and are strongly dependent on efficient sorting schemes to improve current low levels of recycling rates. The gravimetric composition of the MSW selective collection in Brazil highlights the predominance of paper and cardboard, followed by plastics and a large amount of rejects. PET and polyolefins (HDPE/LDPE/PP) correspond to almost 90% of the total recyclables among the plastics category, although the presence of non-identified commingled plastics used in multilayer packaging also represent a significant slice of the PCP waste [17].

The MSW generated by households in the São Paulo city is collected by the selective (dry waste) and the overall (organics, recyclables and non-recyclables mix) collections. In the former, the MSW is separated by category in manual or automated sorting plants operated by cooperatives, for further recovery by the recycling industry. The residual MSW are disposed in sanitary landfill as rejects. In the latter case, a total amount of 98% of the MSW generated in the city is currently being sent directly to sanitary landfills. Since 2020, the automated sorting plants, or MRFs,
processed around 50% of the total MSW selective collection of the city. However, the efficiency and relevance of such imported equipment to the local MSW collection system are still unknown in Brazil.

Negative externalities produced by the presence of increasing amount of recyclable rejects in MSW selective collection in a Brazilian material recovery cooperative have been investigated by [18]. The research has showed the importance of the source segregation of the selective collection by households and the large amount of potentially recyclables ending up as rejects owing to inexistence of commercialization markets for them. In the case of PCPs, separation, sorting and recycling possibilities are essential for the waste management and improvement of recovery yields as shown by [19]. Whether MRFs can be customized to tackle the challenges posed by increasing complexities of post-consumer waste segregation and recovery remain an open question to further research.

This study presents the characterization of the mass flows at the two MRFs located in São Paulo City, in attempt to show that post-consumer plastic waste introduces further complexities in the sortation of well-established recycling streams that MRFs were designed for, in the biggest city in Latin America. The work was designed to provide information about the composition of waste mixes from selective collection reaching out to the facilities over 1-year period through some programmed random samplings, used for gravimetric analysis and calculation of materials recovery yields after the screening process. The research discusses problems related to source segregation of selective collection by households and current limitations and challenges posed to both MRFs capabilities in Sao Paulo City to sort out post-consumer plastic waste and reduce the amount of residual waste from MRFs outputs, which are sent to landfills as rejects.

### Data source and methodology

#### Scope of the solid waste management in São Paulo city

The selective collection is carried out either through door-to-door and pick-up points, which are known locally as PEVs or Ecopoints. In 2017 and 2018, around 40% (38,400 ton/year) of the selective collection were shipped to the two existing MRFs, which corresponds to 17 out of the 32 sub-municipalities in the whole city. The other part (55,000 ton/year) were shipped to 20 cooperatives (manual sorting plants), spread over most of sub-municipalities. Each MRF are operated by a concessionaire, like LOGA—Logística Ambiental, responsible for the Northwest Region of the city and ECOURBIS Ambiental, responsible for the Southeast Region of the city (Fig. 1).

Figure 2 presents the flow of materials from the MSW selective collection after arriving at the MRFs.

#### LOGA MRF—capacities and operation

The LOGA MRF located in Northern the São Paulo City is managed and operated under concession by Logística Ambiental S/A (LOGA) since 2012. Its nominal installed capacity is 250 tons/day, although within the period of the present study it was processing only 80 tons/day, 20 days per month, or just 32% of its full capacity.
The LOGA MRF technology employs optical, magnetic and physical devices for sorting waste by type, size, volume and even color of the waste. Notwithstanding its sophisticated sorting system, the MRF also requires human labor to spot recyclables or contaminants that were overseen by the devices or escape the sorting system.

The LOGA MRF operation process begins with the reception of loaded trucks with source separated MSW recyclables from door-to-door selective collection which is first weighed by large capacity scales. A control ticket containing information about the amount of waste, time and date, as well as its source, is issued for every truck for tracking purposes.

Furthermore, the truck is driven to a discard area for the MSW selective collection, where its contents are spread all over the ground for a preliminary screening of organic waste or any other type of waste not handled by the facility, which are disposed in a transshipment dump. At this step, some workers perform a preliminary manual collection over the waste stacks to remove visible empty bottles and glass bottles, which are then, stored into 200 L capacity bales. The input mixes are pre-loaded on the conveyor belts using bulldozers for removal of bulk and large items (above 350 mm), before being conveyed to the rotating sieves. The waste is segregated by particle size according to the mesh of the rotating sieves and in this step, particles minor than 80 mm, such as sand, and organic wastes are disposed via conveyor belts into the rejects dump.

According to their typology, the medium items (between 80 and 350 mm) are conveyed downstream to the first automated sorting device named ballistic separator, where the materials are sorted by mass and shape. The flat ones (two-dimension, or 2D) are composed mainly of papers, flexible plastics/films and cardboards, and those known as rotating (Three dimension, or 3D), composed of plastic bottles, pots, aluminum cans, multilayer packaging, and so forth.

PCPs are grouped by type after screening by optical devices which sort them out according to their resin identification code 1–7 (1-PET, 2-HDPE, 3-PVC, 4-LDPE, 5-PP, 6-PS, and 7-Others). Paper and cardboard are also screened by optical sensors, and after manual sorting and compression are ready for commercialization, as shown in Fig. 2.

The quality control of recyclables is carried out manually all along the conveyor belts to reduce contamination and improve the MRF recycling yields.

During the present study, LOGA MRF commercialized the following recyclable categories: paper, cardboard, Tetra Pak®, ferrous metal, non-ferrous metal, glass, PET, HDPE, PVC and PP.

**Ecourbis MRF—capacities and operation**

The Ecourbis MRF, installed in the Southeast Group is managed and operated under concession by Ecourbis Ambiental S/A since 2014, and occupies an area of 4,820.97 m² and it has a nominal processing capacity...
of 250 tons/day, although, like LOGA MRF, within the period of the present study it was processing only 80 tons/day, 20 days per month.

Similarly, to the LOGA MRF, the loaded trucks are weighed upon reception before discard of the recyclables for screening and tearing of the collecting bags. After bags are torn apart by a bag tearing device equipment the recyclables are conveyed to a rotating sieve named Trommel, which separates the material into three size classes. Items up to 90 mm (small), items from 90 to 250 mm (medium) and larger than 250 mm (large).

At the Ecourbis MRF, the MSW from the selective collection is handled by three Trommel sections into their respective streams. Materials screened in the first stage section are classified in a vibrating table by specific gravity to recover more dense valuable materials, such as glass and metals. Materials screened in the second stage are segregated by a two-section disk screening and air-blow classification system. In the third section, large size objects are manually sorted, particularly half-gallon and gallon size metals, glass and plastic containers which are conveyed for further processing.

After leaving the Trommel, the small items are conveyed to the magnetic and induction sensors, which are responsible for separation ferrous and non-ferrous metals. Materials which do not fall in none of the two categories are dumped as rejects. Meanwhile, the large items are conveyed directly to manual sorting, where valuable items are removed manually from the conveyor belts for recycling. Medium size items in the range of 90 and 250 mm are further to the ballistic device which separates the materials by weight and shape in a vibrating ramp. As though, 2D items such as flexible plastics and films, papers, shopping bags and the like made out of Low Density Polyethylene (LDPE) are segregated from the 3D items, such as beverage bottles and other products made out with PET, cleaning and hygienics made out of High Density Polyethylene (HDPE). The items which do not fall within both categories are conveyed to the reject output.

As illustrated by the flowchart in Fig. 2, the 2D items (flat) are furthered to the optical sensor 2D, where they are separated as paper, plastic film and cardboard. All the steps are followed by manual sorting and removal of contaminants from the recyclable’s streams before shipment for commercialization.

The 3D-items shown in the flowchart are then furthered to 3D optical sensor to be sorted by PET, HDPE and others. In the case of PET items, they are sent to another optical sensor to be separated by color before being sent to manual sorting for removal of contaminants. Similarly, the recovered HDPE’s are sent for manual sorting and removal of valuable items to be bailed for commercialization.

During the present study, Ecourbis MRF commercialized the following recyclable categories: paper, cardboard, Tetra Pak®, ferrous metal, non-ferrous metal, PET, HDPE and LDPE.

**Sampling methodology**

The strategy for the collection of samples was established to characterize the input and output materials after technical visits carried out at the two MRFs. The samplings aimed to carry out in situ comparisons on specific dates, to find what was being sorted out and effectively generated as rejects. Therefore, a collection schedule was established every 2 months, but at the same week for each MRF and at different days of the week and times, to cover the different sub-municipalities served by the selective collection, as proposed by [21]. Table 1 shows the 7 sampling campaigns carried out for each MRF, covering the period from May 2017 to May 2018, and the corresponding sub-municipalities.

Therefore, three collection points were established in each MRF, two of them located at the input mix (E1 + E2), “as received” from households’ selective collections and one at the output (S), after the entire mechanical and manual screening process had been carried out, as depicted by the flowchart in Fig. 2:

a. E1: garbage bags “as-received” from households are sampled at the unloaded piles from the selective collection trucks, totaling 35.5 kg for MRF Loga and 30.9 kg for MRF Ecourbis throughout the study;

b. E2: this is the same waste above, but now mixed after passing through the tearing bags device, just before loaded into the first conveyor belt, totaling 35.3 kg for MRF Loga and 40.3 kg for MRF Ecourbis throughout the study;

c. S: total rejects collected at the output of the mechanized and manual sorting process. S also includes portions of contaminated or non-sorted recyclables, which are added to the actual rejects, totaling 26.9 kg for MRF Loga and 60.7 kg for MRF Ecourbis throughout the study.

Small quantities of MSW were collected at random to represent as much faithfully as possible the total waste processed by the facilities over the scheduled collections. The collection campaigns were designed to be most representative of all sub-municipalities attended, following standard procedures [22, 23]. After collections, the samples were transported at the same day to the laboratory where they were stored at room temperature for the gravimetric analysis.

**Gravimetric analysis**

To perform the gravimetric analysis in laboratory, the waste from each sampled bag (E1 or E2 or S) were spread on a
plastic sheet on a bench, as shown in Fig. 3, for the main PCPs typologies. The procedure consisted of a careful visual and manual sorting of the recyclables, in similar classes and determination of the mass of each group in terms of 22 different typologies, as listed in Table 2. These 22 typologies were defined based on the class of materials commercialized by the manual sorting plant to the local recycling industries, as proposed previously by [24]. After segregation, each typology was weighed and stored at 4 °C for future characterization analyses.

### Materials recovery yields

Hotta et al. (2016) highlighted the challenges for standardized measurement of recycling rates and target setting as in many countries recycling rates take many forms and levels of waste recovered, such as recovery rate, collection rate, diversion rate, and cyclic use rate. As emphasized by the authors such diverse definitions and lack of standardized measurements for the recycling rate often require careful treating of the recycling rate value to avoid incorrect or confusing comparison and interpretation [25].

In the study, Material Recovery Yield (MRY) was calculated from the total amount of the averaged recyclable waste for each category plus the total amount of the corresponding residual recyclable waste, which was sent to the landfill, as represented by Eq. 1:

\[
\text{MRY}_i = \frac{\sum R_i}{\sum (R_i + L_i)} \times 100. \tag{1}
\]

Or in terms of the collection data:

\[
\text{MRY}_i = \frac{\sum (E_1 + E_2)}{\sum (E_1 + E_2) + \sum S_i} \times 100, \tag{2}
\]

where: \( R_i = (E_1 + E_2)_i \) = total amount of recyclable waste category at the collection \( i \); \( L_i = S_i \) = total amount of the corresponding residual recyclable waste sent to the landfill; \( n = \) Total number of collection campaigns performed at each MRF \( (n = 7) \).

Similar approach for calculation of materials’ recovery rate in terms of materials flows and residual recyclable waste after screening process is presented by [26].
Results and discussion

Figures 4 and 5 depict the gravimetric results for the input \((E_1 + E_2)\) and output \((S)\), respectively, for each class of waste at LOGA and Ecourbis MRFs over a period of 7 collections campaigns \((C#)\) along 1-year time span.

By considering the averaged input \((E_1 + E_2)\) collections illustrated by Fig. 4, a high concentration of certain typologies stands out very clearly: paper/cardboard, plastics, glasses and metals. Altogether those classes of materials represent most of the total sampling collection at both MRFs. A high concentration of paper/cardboard, plastics and glass may result from selective collection and recycling campaigns which improves the sorting efficiency at the collection source, as can be seen their reduction in output \((S)\), Fig. 5. In the case of non-ferrous metals such as aluminum cans, they were hardly found at the collection sampling once they are collected upfront by waste pickers and sold directly to reprocessors, even before reaching out the selective collection or the MRFs.

Gravimetric data from the output collection \((S)\) depicted in Fig. 5 represent the materials that goes to the sanitary landfill as “rejects”, indicating that a considerable amount of potentially recyclable materials is still being shipped to landfills. This may result from part of the recyclable materials being overseen by the optical sensors at the ballistic stage, and as though, they are not segregated by the sorting devices, and may have also been skipped in the manual collection.

Figures 6 and 7 depict the detailed gravimetry at input and output collections, respectively, for each category of screened PCP for both MRFs. As expected, PET leads the concentration of the most preferred plastic materials for recycling, followed by HDPE and PP. Market value at least for PET and HDPE bottles result from their high sortability by optical and ballistic devices. In the case of PP, strong post-consumer resin markets seem to be emerging, although not much robust yet apart the well-established streams for labels and bottle caps. A fair amount of non-identified or unknown commingled plastics was found either in both input and output collection after the screening and sortation process. This category is most comprised of multilayer films and flexible plastics which may cause operation problems in the MRF and drop in the sortation efficiency, as though, reducing the value of other recyclable streams, notably paper and cardboard [27]. The lack of code identification in plastic packaging hampers their sorting for recycling, and as such, they are bound to be classified as rejects.

The Materials Recovery Yield (MRY) for each class of waste and PCPs category were calculated using Eq. 2 and summarized in Table 3.

It is important to remark that both samplings \((E_1 + E_2)_i\) and \(S_i\) were collect at the same day, but may not necessarily represent the same screened waste at the input and output of the process. Consequently, some variations on MRY values may have occurred as a result of uncontrolled changes in the balance flows.

The best performances for MRYs in both facilities were found for paper, cardboard, Tetrapack\textsuperscript{®}, which are materials with well consolidated recycled markets and are commercialized by both facilities. The same was observed for the ferrous and non-ferrous metals such as aluminum, which have a good market value. Among the evaluated PCPs categories, the largest MRYs were found for PET, HDPE/LDPE and PP-based products. In overall terms, the Plastic Recovery Yields at Ecourbis MRF has shown better performance than LOGA MRF. The difference between both facilities could be explained in terms of the Trommel device, mainly in relation to the classification of large items, which is done manually at LOGA MRF. At Ecourbis MRF, the 3D items recovery, such as plastic bottles and flasks are most comprised of the PET and HDPE/LDPE categories and eventually some PP-based products. The latter have a broad range of applications in the packaging and consumer industry but may be mistaken by HDPE if not well identified by the...
recycling ID label. As such, MRY for PP will vary depending on the MRF setup capabilities and its waste recycling goals, as observed in Fig. 5 and Table 3. The same applies to Styrofoam, although PS-based products presented low recovery yields at both facilities owing to their low density and level of contamination of mostly food-contact items. Nonetheless, even for more consolidated recyclable streams there were significant losses in terms of residual recyclable waste which are sent to landfills as rejects according to Table 3. The results suggest failure in the mechanized sorting process at both MRFs, which may stem either from contaminated waste at the source, lack of proper material identification or operational faults [28].

Both facilities have presented glass recovery yields of 53.25% and 30.62% for LOGA and Ecourbis, respectively. In spite of glass was commercialized by LOGA, the presence of glass in the selective collection of São Paulo City tends to disrupt the sorting process in the MRFs as their equipment were imported from countries where the glass waste collections is handled apart from mainstream recyclables. High levels of glass in the input mix from selective collection contribute to increasing the volume of rejects in the output as glasses are high-density materials and their value in the local recycling market is comparable low [18]. Conversely, TetraPack® is a large used container that replaces glass bottles for juices and beverages with good value in the local recycling market, which reflects in their relatively high MRY values from both MRFs. In Brazil, reuse of TetraPack® packaging waste used in low-income house roofing is a good example of well-established recycled markets to boost recovery rates [29].

The high presence of plastics in the input and output of both facilities were mostly comprised of packaging, such as shopping bags, beverage and cleansing bottles and non-identified commingled plastics. Nonetheless, although representing a high volume of packaging and replacing many other types of materials, plastics waste have a recovery rate strongly dependent on the type of product (rigid or flexible) and on the type of resin which they are made of.

### Table 2 Detailed typology adopted for gravimetric analysis of the MSW from selective collection

| Number | Typology—Level 1 | Description—Level 2 |
|--------|------------------|---------------------|
| 1      | Paper            | Paper packaging, office paper, magazines, newspapers, among others |
| 2      | Cardboard        | All types of packaging or cardboard fragments, of all colors |
| 3      | Non-ferrous metals | Aluminum: beer and soda cans, frames, wrapping foil |
| 4      | Ferrous metals   | Steel cans for food, iron components, stainless steel pans among other components made of iron and steel (magnetics) |
| 5      | Tetra Pak        | Milk and juice packaging, made of aluminum, cardboard and plastic |
| 6      | 1—PET—Polycarbonate | Water glasses and beverage bottles, dairy products pots (butter, cream cheese and margarine) |
| 7      | 2—HDPE—High-density polyethylene | Cosmetic, cleansing and hygiene products pots (Shampoo, detergents, softeners) |
| 8      | 4—LDPE/LDPE—Low-density polyethylene | Food packaging (bread bags), shopping and supermarket bags, flexible plastics packaging in general |
| 9      | 3—PVC—Polyvinyl chloride | Pieces of water and sewage pipes |
| 10     | 5—PP—Polypropylene | Food pots, like yogurts and smoothies, and bottle caps |
| 11     | 6—PS—Polystyrene | Disposable plastic cutlery, disposable/single-use cups |
| 12     | 7—Others | Plastic packaging with the label indicating the number 7 (“others”); usually, mix plastic with or without other materials, like aluminum |
| 13     | Non-identified plastics | Plastics without any label; unknown or unrecyclable; EPS food packaging; all plastics above contaminated and without label |
| 14     | Styrofoam—Expanded polystyrene | Food and home appliances packaging |
| 15     | Glasses          | Clear glass, brown glass, green glass, other glasses (home, pots, bottles) |
| 16     | Textiles         | Clothes (jeans, shirts, shirts, underwear, cottons), rags, used cloths |
| 17     | Leather          | Belts, shoes pieces, rugs, etc |
| 18     | Rubber           | Shoe soles, sandals/rejects from bicycle tires and wheels |
| 19     | Wood             | Wood packaging, treated wood, demolition woods |
| 20     | Electronics      | Small home appliances, electronic equipments, CDs, batteries, ear buds |
| 21     | Hazardous        | Medicines, automotive oils packaging, needles and syringes, lamps |
| 22     | Rejects          | Rejected food (vegetable and animal food waste), rejected garden waste (humid soil, plant material and animal straw), dead animal and animal excrements, used napkins, diaper |
Research collaboration carried out by Materials Recovery for the Future Project [30] has demonstrated through pilot studies that a MRF equipped with state-of-the-art sorting devices and fed with flexible packaging collected loose by households could capture at least 90% of flexible plastic packaging while reducing paper/fiber contamination for reprocessing into recycled content products. Performance indicators can also be useful to measure the effectiveness and the efficiency of MRF fed by mixed packaging waste. They provide further support for decision making with respect to demand and plant lay-out improvements of some plastic categories showing poor performance such as LDPE and PP multi-layered films which are hard to recover from fast moving conveyor belts [31]. Consequently, in thesis any MRF can be tweaked using performance indicators to improve their sorting capabilities and increase their recovery yields, although pre-sortation of selective collection by households should always contribute to a more positive outcome.

Interestingly, hazardous materials showed high MRY, even though they are not officially marketed by both MRFs, and rubber, given seasonality, did not present consistent data. Low values for rejects were expected (12 to 23%).

**Research implications and outreach**

The most important technology route for PCP recovery in Brazil is mechanical recycling, whereas chemical methods remained rather incipient to the time of the present research.

---

**Fig. 4** Gravimetric distribution of the main types of waste present in the input collections (E1 + E2), where C# is the collection campaign number: a LOGA MRF; b Ecourbis MRF
Best practices for recycling plastics require that they are properly separated and washed before reprocessing, although washing is not considered a full decontamination process for food-contact packaging and/or cosmetics. The present work has identified a large number of plastic reprocessors which benefit from sorted recyclables yielded by the MRFs and are located within a perimeter of 4 to 32 km from the facilities, whilst the municipal landfill which receives the rejects is located at 18 km. Waste pickers and manual cooperatives also play an important role in plastics recovery for recycling in Brazil, as shown in recent work by [11].

The post-consumer recycling rate (PCRR) is another parameter that helps gauge the demand for PCPs. In Brazil, in 2012, the PCRR was estimated at 20.9% [32] and the average recycling rate of plastics has grown steadily in Europe and has reached 40% in most northern countries [33].

However, due to high volatility in demand and market value for the main resins, there are big gaps in PCRR values which may range from as high as 50% for PET and HDPE bottles to as low as 2–3% to multilayer plastics and Styrofoam. How MRFs technologies may contribute to improve recycling indexes remain object of intense research to fill the gap between the growing demand for PCRs and their current low level of supply [13].

The concentration of rejects at the input and residual recyclable waste at the output collections depend on sortation and classification criteria which may vary considerably depending on MRFs capabilities and recycling goals [34]. The percentage of rejects from a properly operated MRF supported by effective public outreach and educational programs should not exceed 10% by weight of the total outputs of the facility, albeit in practical terms these figures are

---

**Fig. 5** Gravimetric distribution of the main types of waste present in the output collections (S), where C# is the collection campaign number: a LOGA MRF; b Ecourbis MRF

### Table 1

| Waste Category      | Accumulated Collection, wt.% |
|---------------------|------------------------------|
| Rejected (grasses, sand, napkins) | 10/10/0/1/0/0/0/0/0 |
| Paper               | 10/10/0/0/0/0/0/0/0 |
| Cardboard           | 10/10/0/0/0/0/0/0/0 |
| Tetrapak            | 10/10/0/0/0/0/0/0/0 |
| Non-ferrous metals (A1 cans) | 10/10/0/0/0/0/0/0/0 |
| Ferrous metals (iron, steel) | 10/10/0/0/0/0/0/0/0 |
| Glass               | 10/10/0/0/0/0/0/0/0 |
| Plastics            | 10/10/0/0/0/0/0/0/0 |
| Hazardous           | 10/10/0/0/0/0/0/0/0 |
| Electronics         | 10/10/0/0/0/0/0/0/0 |
| Wood                | 10/10/0/0/0/0/0/0/0 |
| Rubber              | 10/10/0/0/0/0/0/0/0 |
| Leather             | 10/10/0/0/0/0/0/0/0 |
| Fabrics             | 10/10/0/0/0/0/0/0/0 |

---

**Fig. 6** Gravimetric distribution of the main types of waste present in the output collections (S), where C# is the collection campaign number: a LOGA MRF; b Ecourbis MRF
usually underestimated, particularly with increasing content of PCPs in the selective collection.

In the case of PCPs, manual sorting also yields more rejected materials and misses a considerable portion of the HDPE/LDPE and PET plastics, let alone other types of plastics due to inability or lack of technical skills of waste pickers to segregate them according to their resin typology. In practice, it is extremely difficult for waste pickers to distinguish between very similar PVC and PET bottles relying on their naked eyes, but these resins can be separated quickly and accurately by MRFs optical sorters, as those used in the present study. Nonetheless, a pre-sorted selective collection that reaches the MRFs tend to be less contaminated, which contributes significantly to improve the performance of MRFs in sorting specific types of PCPs for further commercialization. Rodrigues and Mondelli (2021) assessed different waste treatment technologies, such as incineration, composting and conversion of current MRFs in mechanical biological treatment units (MBT), for integrated MSW management in São Paulo City using Multi-Criteria Decision Analysis (MCDA). Their results have shown that the best scenario to increase the materials’ recovery and reduce the current landfill in 70%, considering environmental, financial, social, and technical factors is maintaining 2% of selective collection added by 4 MBTs [35].

Variations in the concentration of rejects from MSW depend upon many factors such as the population awareness, campaigns outreach, operation yield of the waste
pickers, market conditions to absorb the recyclable materials, reduced level of contamination and recovery of new materials and incentives for opening new reprocessors [36]. Contamination of PCPs with food and cross-contamination of different types of plastics increase the amount of rejects in the MRF output, and consequently the costs of further recycling, with negative impact on the quality of the recyclables and its market price. Market forces may also be influenced by global events such as China recent ban on plastic waste imports from western countries, which have completely redesigned the demand for PCPs in North America and Europe [37].

The majority of MRFs are designed to process ordinary, uncomplicated pre-sorted materials that have high market demand such as steel and aluminum cans, cardboard, glasses and certain types of plastics, such as PET and HDPE bottles which tend to present a positive output in terms of MRY. On the other hand, when it comes to a broad range of PCPs, the materials complexities are continually evolving, and it is difficult for MRFs to keep in pace with emerging materials streams without compromising the recycling yields of the facilities. In this regard, strengthening and supporting community programs is critical to maintaining an efficient selective collection that can reduce contamination of pre-sorted

---

**Fig. 7** Plastics gravimetry by type for the output collections (S), where C# is the collection campaign number: a LOGA MRF; b Ecourbis MRF

| Plastic category | Accumulated collections, wt.% |
|------------------|------------------------------|
| Non-identified Plastics | C#01 C#02 C#03 C#04 C#05 C#06 C#07 |
| Styrofoam | 2/12/13/2/9/1/1 |
| Others | 5/15/5/1/2/0/0 |
| PS | 2/2/2/0/1/1/1 |
| PP | 20/20/4/1/3/1/2 |
| LDPE | 1/3/25/2/5/2/3 |
| PVC | 0/0/0/0/0/0/0 |
| HDPE | 38/7/0/1/5/0/2 |
| PET | 12/25/2/5/2/1/2 |

---

**Fig. 7** Plastics gravimetry by type for the output collections (S), where C# is the collection campaign number: a LOGA MRF; b Ecourbis MRF

| Plastic category | Accumulated collections, wt.% |
|------------------|------------------------------|
| Non-identified Plastics | C#01 C#02 C#03 C#04 C#05 C#06 C#07 |
| Styrofoam | 3/13/7/3/10/3/3 |
| Others | 56/24/1/1/7/1/0 |
| PS | 0/4/2/0/2/2/1 |
| PP | 6/5/4/3/6/10/1 |
| LDPE | 3/6/11/12/6/13 |
| PVC | 0/0/1/0/2/0/0 |
| HDPE | 10/2/0/7/1/6/2 |
| PET | 21/11/18/16/18/22/26 |
recyclables before reaching the MRFs, and consequently improve their performance and public reliance on the efficiency of the recycling system [38]. Gadaleta et al. (2022) have also applied the MCDA in the city of Bari in Italy [39]. As opposed to the results obtained by Rodrigues and Mondelli, the most sustainable scenario was the one that increases the selective collection up to 70–80%. This difference could be explained by observed difficulties to guarantee a good quality of the inputs, without cross-contamination coming from the households. The high costs of the door-to-door selective collection, distances involved in a large city such as São Paulo, along with outreach Environmental Education programs to the population, revealed that converting current MRFs into MBTs units is the fastest solution to reduce current levels of sanitary landfills.

According to MRFs surveyed by the Association of Plastics Recyclers [40] in the USA, higher concerns lie over packaging waste with very low or no market value (e.g., mixed paper and codes 3–7 plastics), and materials that disrupt operations (e.g., flexible films, multilayer packaging and shrink-sleeved packages). Increasing volumes of non-identified waste entering the MRFs as contaminants usually disrupt operation, compromise material recovery yields and increase the facility operational costs. Recent campaigns and management waste programs tend to put more pressure on brand owners and manufacturers on considering the marketability of their products from cradle-to-cradle within a circularity concept, once investments in sortation technology to segregate complex PCPs is not offset by a resulting quality improvement in the recovery yields, such as observed for 3–5 coded plastics [41]. The end-of-life solutions deployed for such plastic waste typologies is another important factor that should also impact MRY of low value plastic waste, and consequently the role of MRFs in PCP waste management. In this regard, the benefits and drawbacks of thermal treatment over recycling have been scrutinized by some authors in the light of circular economy concepts and must be considered in future research as it should have impact on current levels of plastics recycling rates [42, 43].

In Brazil, there are no tax incentives to support recycling infrastructure and most pre-sorting selective collection is performed by associations and cooperatives of waste pickers. Due to inherent complexity of PCP reprocessing, the cost of dealing with contamination by recyclers is usually high and is not often covered by the market value of PCRs, particularly in times of oversupply of low-cost virgin resins caused by plummeted oil prices. Actual figures on yield losses due to contamination are hard to be found in the literature, but an estimate in the USA and Europe ranges between 14 and 37% of the weight of the bale sales to recyclers. However, actual figures also depend on specific material recovery yields, as shown by the present study. As a result of increasing packaging waste complexities and lack of robust pre-sorting selective collection, the amount of contamination in PCP is bound to contribute significantly to low recovery yields of most plastic categories and a high rate of rejects observed at both facilities.

Apart from technical and operational MRF features, the research identified some outreach factors which could be implemented over the MSW chain to improving MRY values which are listed as follows:

(a) Proper cleaning and sanitizing of PCP packaging prior to reaching out the selective selection and the MRFs;
(b) Public education campaigns about types of materials they must segregate at the source for selective collection;
(c) Consumers’ information about the timetables of selective selection and location of curbside spots ("PEV") is important to increase the collection of recyclables;
(d) In Brazil, the waste collection system follows the CONAMA Resolution 275/2001 [44], which establishes a bin color system for each class of waste. Often, consumers get confused over which bin they should discard their waste and cross contaminate different types of waste with undesirable effects on MRY. These effects were identified as twofold: (1) more organic residuals

| Table 3 | Materials recovery yields (MRY) at São Paulo’s MRFs (%) |
|---------|------------------------------------------------------|
| Overall waste | LOGA MRF | Ecourbis MRF |
| Paper | 59.29* | 76.31* |
| Cardboard | 69.47* | 89.89* |
| Tetrapack® | 83.97* | 70.71* |
| Non-ferrous. Al | 65.61* | 80.98* |
| Ferrous metals, steel | 94.83* | 90.09* |
| Glass | 53.25* | 30.62 |
| Electronics | 55.58 | 55.60 |
| Fabrics | 26.84 | 78.18 |
| Rejects (grass, sand, napkins) | 23.65 | 12.45 |
| Rubber | 10.28 | 91.35 |
| Wood | 37.31 | 19.38 |
| Hazardous | 73.55 | 88.58 |
| Leather | 100 | 100 |
| Post-consumer plastics | | |
| PET | 63.95* | 62.61* |
| HDPE | 49.97* | 89.08* |
| LDPE | 54.76 | 51.42* |
| PVC | 0* | 0 |
| PP | 37.58* | 60.03 |
| PS | 20.69 | 23.43 |
| Others | 28.03 | 36.64 |
| Styrofoam | 29.05 | 56.37 |
| Non-identified plastics | 16.23 | 53.46 |

*Commercialized categories by the MRFs
and non-recyclables reaching out to the MRFs through the selective selection and (2) increasing contaminated streams outputs and high rejects rates yielded by the MRFs;

(e) Compaction trucks for transportation of waste improve the economics of the collections of low bulk density materials such as plastics, but on the other hand, it compromises the efficiency of the sortation process with negative impact on MRY. The current compaction level of the selective collect system is kept as low as about 20% of the regular collection;

(f) Technical training of waste pickers to spot recyclable materials other than PET and HDPE/LDPE and PP during manual sorting and quality control at the MRFs;

(g) Proper equipment maintenance helps keeping precision of the mechanized and optical sorting systems at the MRFs;

(h) Introduction of washing facilities for cleansing and sanitizing of flexible plastics packaging at the MRFs, as well as on-site units for grinding and reprocessing should also contribute to add value and improve the MRY performance of some plastic categories with low MRY such as PS/Styrofoam and flexible multilayer LDPE/LLDPE/PP packaging;

(i) Investments on new state-of-the-art optical sorters and peripheral equipment that are required for automated MRF recovery of flexible plastics. The actual economic feasibility of improving MRY for this class of waste will vary based on local recycling policies, transportation and landfilling costs, and market demand for PCRs;

(j) Some regulations for collection and recycling of films and flexible packaging are emerging in Europe under Extended Producer Responsibility (EPR). The Brazilian MSW Regulation Plan enacted in 2012 also includes the EPR for certain types of waste, but not yet for plastic packaging [45];

(k) The two MRFs were imported from Europe and were not designed to handle certain types of waste, particularly glass [46]. The presence of glass in the selective collection of São Paulo City disrupts the sorting process in the facilities and contributes to increasing the amount of rejects in the input mix. Consequently, rejects rates in the output could be much lower if glasses were source segregated by households preventing them to reaching out to the facilities;

(l) Innovation initiatives such as eco-design or Design-for-Recycling should help to improve the recyclability of flexible plastics packaging, and other low MRY waste;

(m) Development of new PCR Markets are also important to leverage yields at MRFs. Many large companies are introducing PCR content goals for their products which should help the procurement and reclaiming for such products at MRFs and consequent positive impact on MRY of plastic waste. This includes PET/HDPE bottle-to-bottle; LDPE/LLDPE/PP film-to-film and other building materials applications, such as composite lumber and alike, which demand not only polyolefins, but PS and PVC waste as well.

**Conclusion**

A real-case study performed in two MRF in São Paulo City have shown limited capabilities for improving sortation of PCP waste from winding up as rejects in public landfills. According to gravimetric analysis performed on input and output collections along 1-year sampling, the yield performance of such facilities is outweighed by inefficient collect systems and lack of well-established PCR markets, since rejects represent 7.4% in the input and 35.6% in the output of the study MRFs, in average.

According to the findings, PCP waste is comprised of a myriad of products with different physical, chemical and technical characteristics which reflected on the MRF potential for sortation and recyclability of each PCP category, represented by 29.1% in the input and 25.0% in the output, from which 12.1% and 30.2% correspond to the non-identified plastics, respectively. The gravimetric analysis has shown that mechanical and optical sorters deployed to separating different types of waste provided high recovery yields above 50% for traditional waste streams such as paper, cardboard, metals and PET and HDPE/LDPE and PP resins among the plastic categories. Recovery yields for PP-based products varied in each facility according to the demand, whereas PS/Styron resins have shown low yields, independent of the facility owing to inexistent recycling market for this type of waste once they are used in supermarket trays for food packaging, which are usually heavily contaminated. Low recovery yields of non-identified plastics result from lack of clear resin label identification, inefficient materials sortation at selective collection sources and poor recognition capabilities of the MRFs sorting devices to target and segregate specific resins; particularly flexible plastic packaging which are hard to segregate and capture some value out of them, let alone their high likelihood to contaminate paper and cardboard streams. Black colored plastics also tends to pass undetected by the optical sensors regardless of the base resin and also contribute to the high level of rejects observed.

The results also indicate that limitations on MRY values are not only dependent on the sortation capabilities of the facilities, but also on extrinsic factors related to the inefficiencies in the selective collection system itself. These factors may be related to some seasonalities related to the selective collection system and fluctuations in market demands for PCPs, which are likely to cause fluctuations in the materials recovery data in both facilities. Packaging design
complexity, multi-layered material diversity, and level of contamination of the post-consumer waste reaching out to the facilities pose further challenges to the recovery capabilities of the MRFs, which are bound to become even more troublesome in the future without an orchestrated waste collection system. In this regard, further research is required to study the influence of source segregation of the selective collection by households and cooperatives to reduce the amount of residual recyclable waste ending up as rejects in the São Paulo’s MRFs.

The study also suggests that recycling of PCPs in the São Paulo city may only thrive if it is supported by strong public policies and full stakeholders engagement in-line with profitable market demand, rather than simply law enforcement which makes waste recycling mandatory. In the presented context, both facilities were operating under their full capacity, and their recovery yields for most PCPs were low, apart from PET, HDPE/LDPE and PP, in face of the amount of rejects ending up in overloaded landfills or leaked as littering into the environment. Finally, the devastating effects of the COVID-19 pandemic in Brazil has boosted disposable single-use packaging and protective equipment (PPEs). Consequently, recovery yields of recyclable PCPs should be further compromised by social-economic factors, once local selective collection still relies on informal waste pickers and manual recovery cooperatives severely impaired by the widespread of the SARS-COV-2 amidst Brazil’s lower income population.

Acknowledgements The authors acknowledge FAPESP (São Paulo State Research Foundation) and CAPES (Coordination for the Improvement of High Education Personnel) for funding this research, to AMLURB (Municipal Authority of Urban Cleaning) for the readiness to receive and support the research and to the REVALORES/UFABC (Strategic Nucleus for Waste Revaluation at the Federal University at ABC).

Author contributions Material preparation, data collection and analysis were performed by MAdO and CJ as part of their master’s degree projects at Federal University at ABC. The first draft of the manuscript was written by CAC in collaboration with GM. All authors have read and approved the final manuscript.

References

1. Statista (2021) Annual production of plastics worldwide from 1950 to 2020. https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/. Accessed 28 Jun 2021.
2. Geyer R, Jambeck JR, Law KL (2017) Production, use and fate of all plastics ever made. Sci Adv 3:e1700782. https://doi.org/10.1126/sciadv.1700782
3. Ellen MacArthur Foundation (2016) The new plastics economy. Rethinking the future of plastics. https://www.ellenmacarthurfoundation.org/publications/the-new-plastics-economy-rethinking-the-future-of-plastics. Accessed 22 Aug 2018.
4. Ellen MacArthur Foundation (2017) The new plastic economy, catalyzing action. https://www.ellenmacarthurfoundation.org/publications/the-new-plastics-economy-catalyzing-action. Accessed 22 Aug 2018
5. Tsiamis DA, Torres M, Castaldi MJ (2018) Role of plastics in decoupling municipal solid waste and economic growth in the US. Waste Manag 77:147–153. https://doi.org/10.1016/j.wasman.2018.05.003
6. Kaza S, Yao L, Bhada-Tata P, Van Woerden F (2018) What a waste 2.0: a global snapshot of solid waste management to 2050. Urban development series. World Bank, Washington, DC
7. Hegberg BA, Hallenbeck WH, Brennan GR (1993) Plastics recycling rates. Resour Conserv Recycl 9:89–107
8. Al-Salem SM, Lettieri P, Baeyens J (2009) Recycling and recovery routes of plastic solid waste (PSW): a review. Waste Manag 29:2625–2643. https://doi.org/10.1016/j.wasman.2009.06.004
9. Malinauskaite J, Jouhara H, Czajczynska D, Stanchez P, Katsou E, Rostkowski P, Thorne RJ, Colon J, Pons S, Al-Mansour F, Anguilano L, Krzyzynska R, Lopez IC, Vlasopoulos A, Spencer N (2017) Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe. Energy 141:2013–2044. https://doi.org/10.1016/j.energy.2017.11.128
10. Ragaert K, Delva L, Van Geem K (2017) Mechanical and chemical recycling of solid plastic waste. Waste Manag 69:24–68. https://doi.org/10.1016/j.wasman.2017.07.044
11. Pacheco EB, Ronchetti LM, Masanet E (2012) An overview of plastic recycling in Rio de Janeiro. Resour Conserv Recycl 60:140–146. https://doi.org/10.1016/j.resconrec.2011.12.010
12. Antonopoulos I, Faraca G, Tonini D (2021) Recycling of post-consumer plastic waste in the EU: recovery rates, materials flows and barriers. Waste Manag 126:694–705. https://doi.org/10.1016/j.wasman.2021.04.002
13. Gundupalli SP, Hais T, Thakur A (2017) A review on automated sorting of source-separated municipal solid waste for recycling. Waste Manag 60:56–74. https://doi.org/10.1016/j.wasman.2016.09.015
14. Cimpan C, Maul A, Jansen M, Pretz T, Wenzel H (2015) Central sorting and recovery of MSW recyclable materials: a review of technological state-of-the-art, cases, practice and implications for materials recycling. J Environ Manag 156:181–199. https://doi. org/10.1016/j.jenvman.2015.03.025
15. Paben J (2019) Recology adds robotics to produce cleaner plastics, Resource Recycling. https://resource-recycling.com/recycling/2019/11/20/recology-adds-robotics-to-produce-cleaner-plastics/. Accessed 21 Nov 2019.
16. PICPlast (2020) Mapeamento do PICPlast sobre a indústria de reciclagem do plástico ganha espaço no valor econômico. Accessed 24 Jun 2020.
17. CEMPRE (2018) The Ciclosoft Survey 2018. Compromisso Empresarial para Reciclagem, São Paulo-SP. http://cempre.org.br/ciclosoft/id/8. Accessed 18 May 2021.
18. Moura JMBM, Pinheiro IG, Carmo JL (2018) Gravimetric composition of the rejects coming from the segregation process of the municipal recyclable wastes. Waste Manag 74:98–109. https://doi.org/10.1016/j.wasman.2018.01.011
19. Dubanowitz AJ (2000) Design of a materials recovery facility (MRF) for processing the recyclable materials of New York City’s municipal solid waste. Master of Science Dissertation in Earth Resources Engineering Department of Earth and Environmental Engineering, University of Columbia USA.
20. AMLURB (2017). A coleta de lixo em São Paulo. Autoridade Municipal de Limpeza Urbana. https://www.prefeitura.sp.gov.br/
