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Production of Solid Recovered Fuel from the Rejected Fraction of Recyclable Materials from Waste Picker Cooperatives: A Case Study in Brazil

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Abstract: This study evaluated the feasibility of producing solid recovered fuel (SRF) from rejected waste from waste picker cooperatives (WPC). Three scenarios using different SRF and petroleum coke proportions in cement kilns were assessed. The samples of rejected waste from WPC were obtained in the city of Florianópolis, Brazil, and their physical and chemical characteristics were determined. Furthermore, the avoided atmospheric emissions by replacing conventional cement fuel with SRF and the costs to implement a SRF facility were estimated. According to the results, 60.29% of the waste from WPC could be used for energy recovery. Out of the materials eligible to produce SRF, 75.26% are made up of plastic packaging and paper. Concerning atmospheric emissions, replacing petroleum coke with SRF for direct feeding into the clinker kiln contributed to a reduction of 4.83%, 14.73%, and 13.37% in the atmospheric emissions for Scenario 1, Scenario 2, and Scenario 3, respectively. Furthermore, considering two hypothetical SRF industrial plants with capacities of 522 and 720 t/day, each ton of SRF produced would cost about USD 6.00, representing a decrease of 35 times in the costs when compared to petroleum coke. Therefore, SRF from the rejected fraction of WPC could be an alternative waste-to-energy approach.

Keywords: municipal solid waste; biomass; waste picker cooperatives; solid recovered fuel; waste valorization

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1. Introduction

Solid waste management faces a series of challenges such as increased production, inadequate disposal, lack of infrastructure for recycling, environmental education, and population engagement in the process. Moreover, it is known that solid waste can pollute soil, water, and air, and its mismanagement is responsible for approximately 5% of global greenhouse gas emissions [1]. Globally, due to the linear economic model, about two billion tons of solid waste are generated annually, and this number is expected to increase by 70% by 2050 [2]. Nowadays, population and economic growth constitute a major challenge in implementing strategies for the reduction, recovery, treatment, and disposal of solid waste worldwide [3].

In Brazil, the National Solid Waste Policy establishes the following order of priority in solid waste management: non-generation, reduction, reutilization, recycling, treatment of solid waste, and environmentally appropriate final disposal of the rejected fraction [4]. However, given the inefficiency of the services to effectively attain these goals, most of the waste is conveyed to dumps or landfills. Landfills, although considered a safe technique for the final disposal of solid waste, significantly increase pollution vectors such as leachate and gases, which require suitable methods of control and treatment [5]. In cities with a developed waste management system, selective collection is carried out, which separates recyclable materials to reintroduce them into the production cycle [6]. Selective collection is one of the stages of a broad integrated solid waste management system, contributing to reducing the environmental impacts and giving the correct destination to materials with the potential for further valorization [7]. In Brazil, selective collection has been developed by municipal authorities or by associations and cooperatives of waste pickers of recyclable materials. The materials regularly collected are paper, cardboard, plastic, glass, and metal [8]. Indeed, the implementation of selective collection systems is directly related to the work developed by waste picker cooperatives (WPC); about 55% of the material collected by the door-to-door system is sent to these places [9]. The process carried out by the WPC presents some flaws, such as incorrect household separation and the existence of materials for which any recycling technology is available in the country, characterizing these materials as waste.

One method for solid waste management is the utilization of materials with high calorific value as an alternative fuel, which agrees with the circular economy concept [10]. Energy recovery is a sustainable way of exploiting the energetic potential of solid waste that would otherwise be disposed of in landfills, causing long-term pollution [11]. Moreover, alternative fuels are generally cheaper than conventional fuels because most of them come from wastes that only present processing and logistical costs [12].

Among the existing alternative fuels, one can cite solid recovered fuel (SRF), which consists of municipal solid waste (MSW) with or without the incorporation of other solid waste (e.g., agricultural and non-hazardous waste) used in energy-recovery processes [13]. The production of SRF requires the elimination of the non-combustible fraction, the reduction in the particle size and moisture content, the homogenization of waste, and in some cases, its transformation into pellets or briquettes [14]. Thus, the SRF can be used in different locations such as industrial boilers, clinker production furnaces, and gasification and pyrolysis reactors [15].

In cement industries, fossil fuels (e.g., petroleum coke) are used in the kilns and in the preheater system to produce the high temperatures necessary to form clinker [11]. These fuels emit carbon dioxide (CO_2) and other gases, such as sulfur dioxide and nitrogen oxide, in addition to generating a dependence on non-renewable resources. Thus, greenhouse gas emissions can be reduced by replacing fossil fuels with alternative fuels, such as SRF, thus reducing the use of natural resources [16,17]. In addition to replacing the energy source, the use of SRF in the cement industry enables adequate waste treatment, since the ash generated in the process can be incorporated into the clinker [11]. Therefore, SRF production has become attractive due to two main factors: the production of relatively cheap and readily available fuels, and treating large amounts of accumulated waste [18,19]. Moreover, SRF has become important to the global energy transition, mainly due to the goals assumed by countries in the Paris Agreement to reduce CO_2 emissions. For instance, using SRF gasification can reduce the environmental impact of MSW landfills and the reliance on natural gas in electricity generation [20]. Incineration plants as well as industrial co-incineration plants have exploited the potential of SRF to fulfill their own heat/electricity demand or somewhere else, which can also benefit economically from placing electricity in the national grid [21]. Accordingly, SRF could be part of the energy source in the cement industries.

Regarding the ideal composition of SRF, it should contain materials with high calorific value, presenting high amounts of plastics, paper, cardboard, polymeric packaging, textiles, and wood. These materials are made of biogenic compounds that increase the calorific value of the fuel while contributing to the reduction in CO_2 emissions [16]. However, given the variability of the MSW characteristics among different cultures, it is mandatory to verify the potential of producing SRF in each country. In Brazil, SRF is a promising sector that is expected to grow due to the edition of the standard ABNT-NBR 16849/2020 from the

Brazilian Association of Technical Norms, which deals with the requirements for using MSW for energy purposes [13].

Therefore, this work aimed (i) to analyze the chemical characteristics of waste from WPC in the city of Florianópolis, Brazil, to evaluate the potential of these materials as SRF; (ii) to report the avoided atmospheric emissions by using SRF instead of petroleum coke in clinker production kilns for three scenarios using different proportions of these fuels; (iii) to estimate the costs of implementing an SRF plant.

2. Materials and Methods

2.1. Sample Collection

The study was carried out in Florianópolis, Santa Catarina, Brazil. The samples were obtained from the rejected fraction produced by three WPC, named herein as A, B, and C, which were responsible for receiving almost 72% of the total recyclable waste collected in Florianópolis in 2020. For sampling, bags with approximately 50 kg were overturned onto the local floor and divided three times by quartering until a sample of 10 kg was obtained. After sample quartering, the gravimetric and granulometric characterization of each sample (A, B, and C) were determined before chemical analyses.

2.2. Sampling Procedures: Granulometry, Gravimetry, and Physicochemical Analyses

The waste was evaluated according to the methodology for the solid waste analysis of the European Commission (SWA-Tool, 2004). The number of samples needed was first determined to perform the analyses. Considering that the waste heterogeneity in Florianopolis was unknown, five random samplings were carried out in the largest WPC to define the number of samples. A coefficient of variation of 25% and a confidence level of 95% was considered, resulting in 24 samples from each WPC for the reliability of the results obtained.

Given that each analyzed site has a large amount of rejected fraction generated (about 20% of the total amount of recyclable waste arriving at the cooperative), 10 kg was collected from each WPC to carry out the gravimetric composition. The samples were obtained by quartering following the standard procedure from the Brazilian Association of Technical Norms (ABNT-NBR 10004/2004), which describes the classification of solid waste [22].

The rejected fraction from the WPC was separated into ten categories to identify its composition and relate it to the calorific value obtained. These were defined based on a visual analysis of the rejected fraction in the WPC, as listed below:

(a) Metallic packaging (e.g., snacks packaging);
(b) Food product packaging 1 (polypropylene (PP) packaging, e.g., pasta and chocolate packaging);
(c) Food product packaging 2 (polyethylene terephthalate (PET) packing, e.g., cake packaging);
(d) Two different materials (packaging made of paper and plastic together);
(e) Styrofoam;
(f) Clothes and shoes;
(g) Organics;
(h) Colored PET packaging;
(i) Paper;
(j) Glass and debris.

It is important to mention that although the organic, clothes and shoes, and glass and debris categories form part of the waste from the WPC, they were not included in the final gravimetric composition to produce SRF. The organics would lead to a significant increase in humidity, in addition to degrading and attracting vectors. Additionally, the clothes and shoes presented high humidity, so their utilization was also avoided. Regarding glasses, they are inert materials.

The granulometry of the samples was measured in a range from 50 to 450 mm in intervals of 50 mm, and a portion of each sample (about 100 g) was segregated to determine the chemical characteristics. The following parameters were determined: lower calorific value and the content of moisture, ash, chlorine, zinc, mercury, and copper. This experiment followed the procedures presented by the standard NBR 16.849/2020 from the Brazilian Association of Technical Norms [13].

The gravimetric fractions were reduced to pieces of about 2 mm to determine the moisture and ash contents. The analysis was carried out in a muffle furnace. For the other analyses, the samples were ground twice in a micro knife mill (Marconi, model MA048) in a stainless-steel screen with a 0.075 mm opening. To determine the calorific value, the crushed samples were pressed to form pellets, aiming to provide greater stability of the material inserted in the calorimetric bomb (PARR, model 6200). The chlorine content was determined using Dionex ICS 5000 equipment. The contents of copper and zinc were quantified using an atomic absorption spectrometer (VARIAN Spectra 250), whereas the mercury content was determined with a Mercur Duo Atomic Fluorescence Spectrometer (Analityk Jena, Model Mercur DUO). For copper and zinc, 100 mg of the sample was digested with 10 mL of H_2SO_4 for 20 min, neutralized with 2 mL of NaOH and 10 mL of distilled water, filtered, and the volume made up to 50 mL with distilled water before analysis in the atomic absorption spectrometer. For mercury, 200 mg of the sample was digested with 5 mL of HNO_3 for 30 min at room temperature. Then, 5 mL of distilled water was added, and the mixture was placed in an ultrasound (50 W and 55 Hz) for 5 min. Following this, it was centrifuged at 3500 rpm for 3 min, and after dilution and stabilization with $KMnO_4$ and NH_2OH, the mercury content was analyzed. The statistical treatment of the results was carried out using the Statistica® software, version 8.0.

2.3. Avoided Emissions

The avoided emissions were calculated considering the utilization of SRF in clinker kilns in three scenarios: Scenario 1 used 15% SRF and 85% petroleum coke; Scenario 2 used 35% SRF and 65% petroleum coke; and Scenario 3 used 55% SRF and 45% petroleum coke. The theoretical emissions of atmospheric pollutants were calculated based on the emission factors for CO_2, CH_4, and N_2O contained in the GHG Protocol Tool (version 2020.1.2) adapted to the Brazilian context by the São Paulo School of Business Administration of the Getulio Vargas Foundation (FGV-EAESP). The Brazilian GHG Protocol Program was created in 2008 to provide a set of calculation tools to estimate greenhouse gas (GHG) emissions in Brazil [23].

For coke, the emission factors of CO_2, CH_4, and N_2O were 3425.96, 0.105, and 0.021 kg/t, respectively. For MSW, the emission factors of CO_2, CH_4, and N_2O were 917.00, 0.348, and 0.0464 kg/t, respectively [24]. The estimate of atmospheric emissions was obtained by multiplying the emission factors by the amount of waste or petroleum coke used in cement kilns. Once calculated, the theoretical emissions were compared among the three scenarios (Scenario 1, Scenario 2, and Scenario 3).

2.4. Economic Evaluation

As SRF is a new technology in Brazil, the available data on the costs of setting up an industrial plant are scarce. Thus, the economic analysis was based on the study developed in the metropolitan region of Curitiba (South of Brazil) carried out by [25] to estimate the costs to construct an SRF plant. That study presents detailed values of the operation and maintenance of a mechanical treatment unit.

To determine the economic value of the SRF, the annualized equivalent investment cost of the following items was considered: mechanical treatment unit, overhead crane, transshipment station, digital road scale with a platform of 9 m × 3 m, land for installation, infrastructure works, environmental compensation, administrative support area, shed of the mechanical treatment unit, permanent stock of imported spare parts, and transshipment shed. The annual equivalent cost (*AEC*) was calculated using Equation (1), for which the capital recovery factor (*CRF*) was calculated using Equation (2) [26]. The cost of the *SRF* is defined by the sum of the AEC of each item divided by the annual production of SRF, according to Equation (3).

$$AEC = IC \cdot CRF + \frac{IC \cdot OM}{100} \quad (1)$$

where AEC, IC, CRF, and OM are annual equivalent costs, investment cost (USD), capital recovery factor, and operation and maintenance fee (%), respectively.

$$CRF = \frac{d}{1 - (1 + d)^{-n}} \quad (2)$$

where d and n are the discount rate or attractiveness rate (herein considered as 0.123) and time of project life (years), respectively.

$$SRFcost = \frac{\sum AEC}{APSRF} \quad (3)$$

where AEC and $APSRF$ are the annual equivalent costs (R$/year) and annual production of SRF (tons), respectively.

3. Results

3.1. Granulometric Composition

From the granulometric analysis of all WPC (A, B, and C), the most representative fractions were in the ranges of 200, 250, and 300 mm, equivalent to approximately 58% of all waste. When adding the fractions of 150 and 350 mm, the total amount of waste was approximately 75% (Figure 1). The mean granulometry was 247.87 ± 163.93 mm, presenting a great variability and indicating the need for a pretreatment (e.g., shredding) to reduce the waste granulometry.

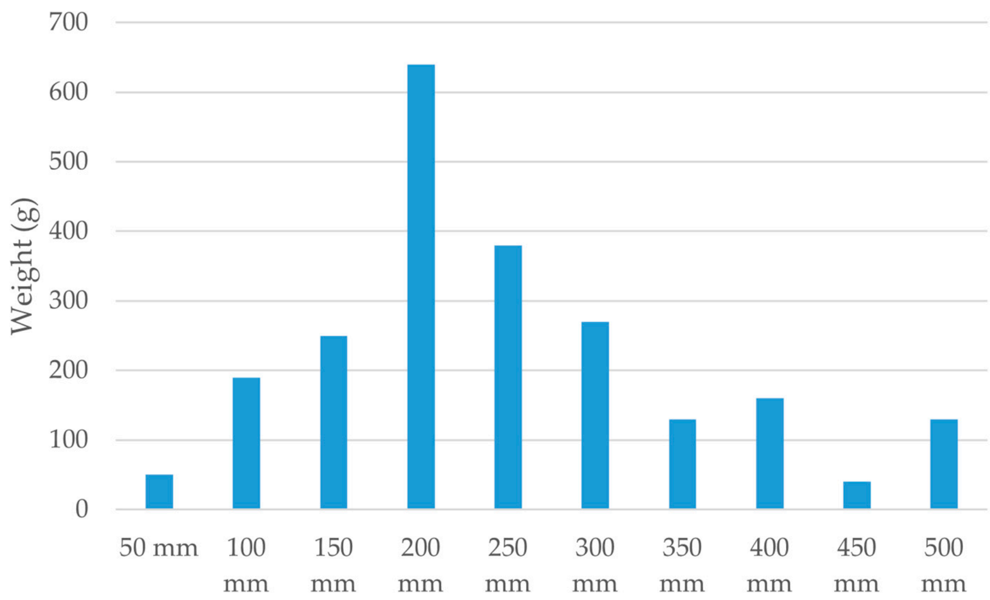
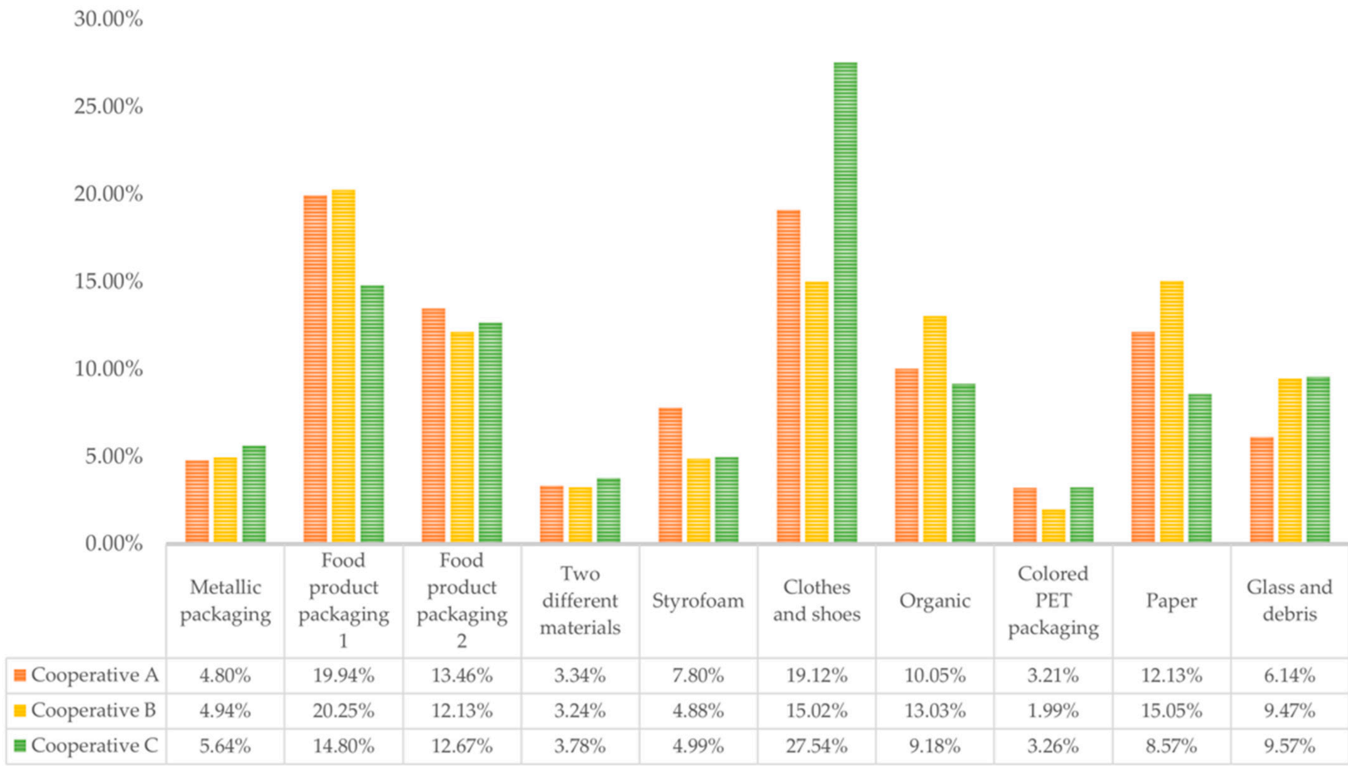


Figure 1. Granulometric composition of the rejected fraction.

3.2. Gravimetric Composition

During the sampling period, materials from different selective collection routes distributed throughout the city were analyzed, representing 84.61% of all the recyclable waste collected and destined for the WPCs. By collecting 72 samples (24 from each WPC), it was possible to estimate the gravimetric composition of the waste from the selective collection, as shown in Figure 2.



	Metallic packaging	Food product packaging 1	Food product packaging 2	Two different materials	Styrofoam	Clothes and shoes	Organic	Colored PET packaging	Paper	Glass and debris
Cooperative A	4.80%	19.94%	13.46%	3.34%	7.80%	19.12%	10.05%	3.21%	12.13%	6.14%
Cooperative B	4.94%	20.25%	12.13%	3.24%	4.88%	15.02%	13.03%	1.99%	15.05%	9.47%
Cooperative C	5.64%	14.80%	12.67%	3.78%	4.99%	27.54%	9.18%	3.26%	8.57%	9.57%

Figure 2. Gravimetric composition of the waste collected by the waste picker cooperatives (WPC) of Florianópolis.

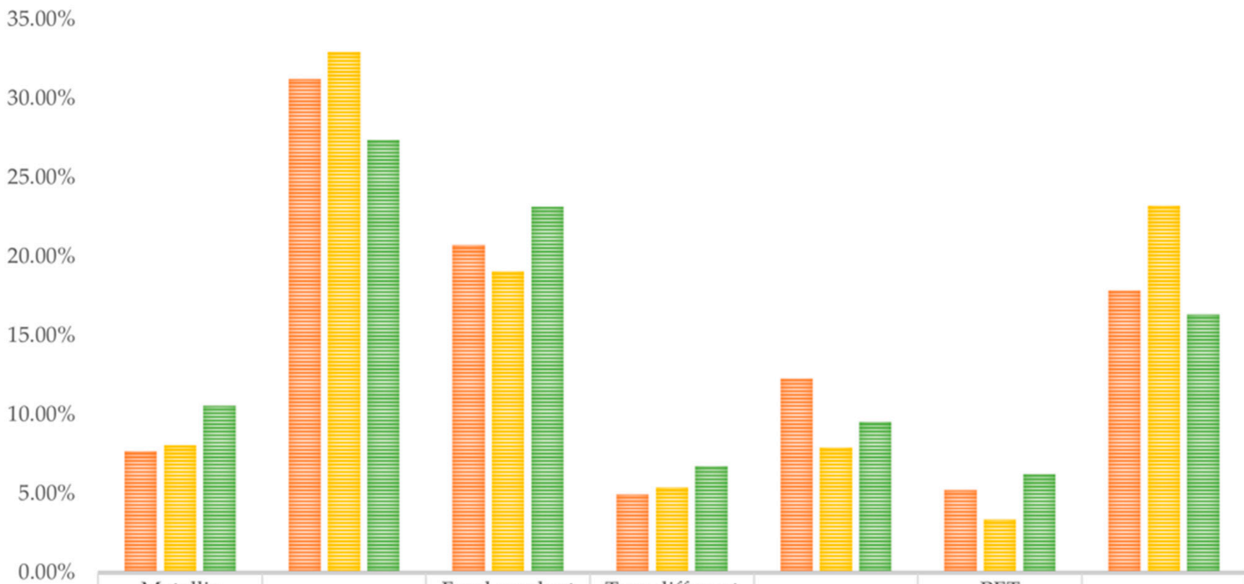
Considering only the combustible fractions—metallic packaging (e.g., snack packaging), food product packaging 1 (polypropylene (PP) packaging, e.g., pasta and chocolate packaging), food product packaging 2 (polyethylene terephthalate (PET) packing, e.g., cake packaging), packaging made of paper and plastic together, Styrofoam, colored PET packaging, paper—of the gravimetric composition and the average of the gravimetric compositions of all analyzed samples, 60.29% of the waste from the WPC in Florianópolis could be sent to the production of SRF. The generation of recyclable waste and its gravimetric composition are influenced by several factors, such as physical, geographic, sociocultural, and political. In this way, selective collection systems are responsible for providing satisfactory levels of MSW recovery, and the systems implemented can be organized in different ways in each country or the same country, as is the case of Brazil [27]. As presented in Table 1, between 2017 and 2020, according to the private data from the company responsible for collecting the solid waste in Florianópolis, the average of the rejected fraction from all WPC was 20.45%. This indicates that about 2,265,000 kg of waste is sent to landfill every year, wasting resources that could be reintegrated through energy recovery.

Table 1. Evolution of the amount of recyclable waste and the rejected fraction in Florianópolis.

Year	Recyclable Waste (kg)	Rejected Fraction (kg)	Rejected Fraction (%)
2017	9840.650	2029.016	20.62
2018	10,340.826	2169.382	20.98
2019	12,775.690	2515.430	19.69
2020	11,436.700	2346.584	20.52

Source: The data were obtained from the company responsible for collecting the solid waste in Florianópolis (Companhia de Melhoramentos da Capital—COMCAP) by request.

Since 60.29% of the materials can become SRF, the WPC of Florianópolis have a monthly capacity to supply 117,896 kg of waste to produce high-quality SRF. By excluding the organic, clothes and shoes, and glass and debris categories, we obtained the gravimetric composition of only the fraction of waste that would be sent directly to SRF production. According to Figure 3, "Food product packaging 1" (PP packing) was the predominant category, indicating the population's consumption habits and the lack of a market for this type of packaging, which mainly consists of packaging for sweets, pasta, bread, and other food products made of PP. "Food product packaging 2" was the second most predominant. There was a consensus among all WPC that the composition of the samples was dominated by the "Food product packaging 1", "Food product packaging 2", and "paper" categories. Altogether, these categories represented an average of 70% and the analyzed samples had in their composition about 75.16% of plastics of different types.



	Metallic packaging	PP packaging	Food product packaging 2	Two different materials	Styrofoam	PET packaging	Paper
Cooperative A	7.69%	31.23%	20.73%	4.95%	12.30%	5.23%	17.87%
Cooperative B	8.07%	32.95%	19.07%	5.39%	7.95%	3.33%	23.24%
Cooperative C	10.56%	27.39%	23.16%	6.74%	9.57%	6.26%	16.32%

Figure 3. Gravimetric composition of the fuel fraction of the waste collected by the waste picker cooperatives (WPC) of Florianópolis.

Even considering all efforts to reduce, reuse, and recycle, there are still fractions that are unsuitable for reutilization, mainly due to economic reasons. Therefore, energy recovery represents an alternative to these fractions when compared to landfills [28]. It is important to highlight that the adoption of waste-to-energy alternatives cannot be treated as the primary solution to solid waste management problems in Brazilian cities. The adoption of a complete system comprising other alternatives is required before sending the waste for energetic recovery approaches such as SRF production.

On the other hand, in a waste-to-energy scenario, SRF could be used as an alternative fuel in the cement industry. This approach not only saves primary sources of energy but also promotes waste utilization, diverting these materials from landfill disposal [29].

3.3. Chemical Characterization of the Proposed SRF

For the chemical characterization of the proposed SRF, the ash, moisture, chlorine, zinc, copper, and mercury contents were determined. Table 2 presents the results.

Table 2. Chemical characterization of the proposed SRF from three waste picker cooperatives (WPC).

Parameter	Waste Picker Cooperative		
	A	B	C
Ash (%)	3.81	3.79	4.35
Moisture (%)	1.89	4.48	3.25
Chlorine (%)	1.81	2.44	1.86
Zinc (mg/kg)	67.90	66.63	62.71
Copper (mg/kg)	-	17.00	-
Mercury (mg/kg)	0.383	0.069	0.152

The ash content indicates the amount of unburned product. In the case of incineration plants, this information is essential to properly manage the ashes [14]. From an environmental perspective, high ash contents can contribute to particulate emissions, whereas from an economic perspective, they can represent additional costs for their disposal. Furthermore, from a social and health perspective, the particulates emitted can cause respiratory problems [30]. The results obtained for the SRF from the WPC were like other studies; one of them identified an ash content of 7.7% [19], while another reported 10.9% [31].

The moisture content of any solid waste intended to produce SRF is one of the most significant properties because of its direct influence on the calorific value. It also indicates the need for additional treatments for the waste. In a study developed in the southern region of Italy, the moisture content of the produced SRF reached an average value of 29.2% [32], while in the study developed in the province of Castellón, Spain, the moisture content was 34.46% [14]. Another work identified an average moisture content of 20% from selective collection waste using containers in central Portugal [16]. As in Florianópolis, and in Brazil in general, the recyclable waste recovery system is different from that in other countries, so no similar studies were identified for a direct comparison of the results obtained.

For clinker production, Cl represents the main technical parameter for the use of SRF since Cl weakens clinker and increases the risk of steel corrosion, in addition to the formation of acid gases and polychlorinated dibenzodioxins [29]. Commonly, the Cl content in MSW mainly comes from plastics (8.25% in dry matter), composites (2.55% in dry matter), fuels (1.25% in dry matter), and food waste (1.17% in dry matter) [33]. The Brazilian reference to limit pollutant emissions from solid waste processing for energy purposes (Urban waste for energy recovery—Requirements) is norm number 16,849/2020, which states that the Cl value cannot exceed 3.0% [13]. According to Table 2, the average Cl results were within the acceptable limits by that standard. The study of Shumal et al. identified Cl contents ranging between 0.03% and 0.43% [10]. In another work, Gallardo et al. presented Cl contents of 0.34% for dry samples of SRF [14]. Bessi et al. reported average Cl levels of 0.30% for SRF produced from waste from a door-to-door collection system in Italy [34]. Brás et al. showed values of 0.49% for SRF from mechanical biological treatment waste and 0.22% for selective collection samples [16]. Therefore, it was observed that the Cl value obtained herein was superior to those mentioned, which indicates differences in terms of the solid waste management and composition between countries.

Regarding Zn, it can come from glasses and plastics, with the lowest concentration found in glasses (55 mg/kg) and the highest concentration in plastics (259 mg/kg) [35]. In another study, a Zn content of 882 $\pm$ 126 mg/kg of dry matter was identified [36]. Zhao et al. showed a Zn content of 18 mg/kg in SRF produced in Singapore [3]. The general average of Zn contents in the present study was 65.75 $\pm$ 26.16 mg/kg, which is lower and higher than the values obtained by [36] and [3], respectively. This difference is due to the differences between countries.

Cu, along with other heavy metals (e.g., Cr, Hg, and Pb), is considered toxic due to its non-biodegradability and bioaccumulation in organisms [37]. In WPC B, the Cu content was not detected in only two samples. In the samples collected at WPC C, the Cu levels were not detected as well as in 18 of the 24 samples from WPC A. However, in the six samples in which Cu was detected in WPC A, the maximum and minimum values were 13.50 mg/kg and 0.5 mg/kg, respectively, with an average value of 5.33 mg/kg in the samples in which Cu was identified. At WPC B, the maximum value identified was 31.00 mg/kg and the minimum value was 1.50 mg/kg, with an average value of 17 mg/kg (Table 2). Shumal et al. identified an average Cu content of 482.49 ± 640.57 mg/kg [10], while Gallardo et al. reported 108.92 ± 45.21 mg/kg [14]. In a study with several components of MSW from Singapore, a Cu content of 23 mg/kg was reported [3]. Another work analyzing the SRF used in a fluidized bed incinerator from household waste, commercial waste, bulky waste, and construction site waste reported a Cu content of 892 ± 230 mg/kg on a dry basis [36]. Therefore, comparing the data obtained herein with the literature, the maximum value identified in the samples (31.00 mg/kg) was lower than that presented in most of the studies analyzed.

Concerning the Hg content, the Brazilian norm number 16,849/2020 (Urban waste for energy recovery—Requirements) requires its determination when characterizing waste intended for energy recovery purposes [13]. The average mercury level in the present study was 0.20 mg/kg, a lower value than those presented in other studies. For instance, Gallardo et al. reported mercury levels of 82.66 ± 29.97 mg/kg in MSW in the Onda region, Spain [14], and Nasrullah et al. showed mercury values of 0.20 mg/kg in SRF produced from MSW [38].

3.4. Environmental Evaluation

3.4.1. Energy Potential of Waste as SRF

The main factor to determine the energy viability of a fuel is its calorific value, which indicates the amount of energy that can be recovered. Figure 4 shows the average higher calorific value (HHV) of the WPC analyzed. The values ranged between 7474.41 kcal/kg and 7636.77 kcal/kg. The highest HHV values were obtained in WPC A, which can be explained by the greater quantity of plastics in the sample from that particular WPC. Additionally, according to the correlation between the different categories of waste and their calorific value, the higher paper content in the sample, the greater the calorific value.

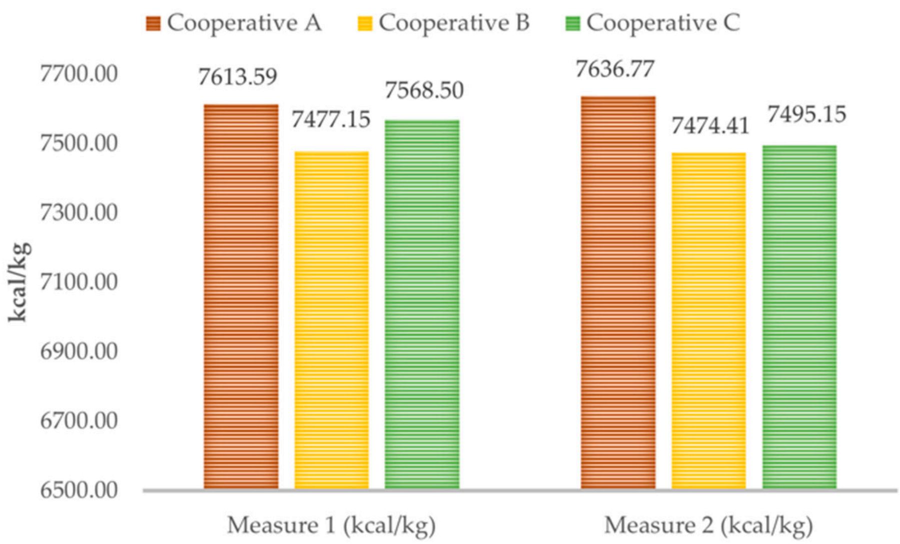


Figure 4. Average higher calorific value (HHV) of the analyzed samples.

The lower calorific value of the samples varied between 5057.20 and 6617.14 kcal/kg. Gallardo et al. presented a calorific value of 4920.23 kcal/kg from a mechanical biological treatment waste plant in Spain [14]. In the study developed in Portugal, a value of 5507.79 kcal/kg was obtained for waste from selective collection [16]. Shumal et al. reported the use of waste from the selective collection as a source of SRF production with a calorific value of 2904.37 kcal/kg, and the low value was associated with the high ash and moisture content of the waste [10]. Therefore, it points to SRF being a promising source of alternative fuel worldwide.

Regarding the eligibility of MSW to produce SRF, European strategies for solid waste management are primarily related to (i) reduction of the generation; (ii) separation at the source of the different fractions that make up MSW; (iii) the recovery and final disposal of the waste [27]. In Brazil, however, the development of the solid waste sector with the government still needs to be boosted so that satisfactory levels of solid waste utilization are reached. This would indeed reduce solid waste disposal in landfills.

3.4.2. Avoided Atmospheric Emissions

The results of the avoided atmospheric emissions are presented in Figure 5, and they were expressed as CO_2 equivalent.

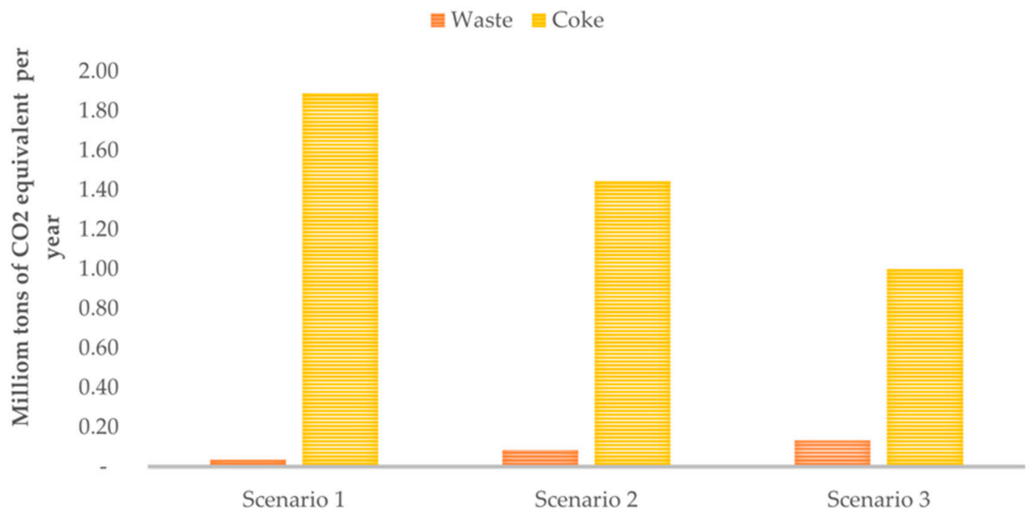


Figure 5. CO_2 equivalent emissions of SRF utilized in clinker kilns in different scenarios (Scenario 1: 15% SRF and 85% petroleum coke; Scenario 2: 35% SRF and 65% petroleum coke; Scenario 3: 55% SRF and 45% petroleum coke).

Replacing petroleum coke with SRF for direct feeding into the clinker kiln contributed to a decrease of 4.83%, 14.73%, and 13.37% in atmospheric emissions for Scenario 1, Scenario 2, and Scenario 3, respectively. This is in line with the provisions from Brazil's Cement Technological Roadmap, which suggests a 33% reduction in emissions from the cement sector as of 2019 [39].

However, emissions may vary depending on the specific characteristics of the SRF used, the combustion processes, and the emission control technologies employed in the cement kiln. In general, when replacing fossil fuel with SRF, it is possible to reduce CO_2 and other atmospheric emissions such as NOx, SO_2, and dust [12].

It is worth mentioning the need for constant observation of the procedures to control pollutant emissions, in addition to an environmental licensing process that establishes appropriate conditions to prevent atmospheric emissions when using SRF. MSW can only be subjected to energy recovery units that have a plan for monitoring the atmospheric emissions of pollutants. In Brazil, that plan must be presented and approved by a competent environmental agency to ensure compliance with the legislation [13].

3.5. Economic Evaluation

The costs were estimated considering the value of one ton of petroleum coke in June 2021 (USD 220.00 per ton) and the American dollar exchange rate against the Brazilian real on 27 June 2021 (USD 4.93). Two scenarios were established to produce SRF: the first considering 522 tons of waste processed per day (Scenario A), and the second considering 720 tons of waste processed per day (Scenario B). Scenario A concerns 50% of the daily waste generation that goes to the landfill for the metropolitan region of Florianópolis, and Scenario B was established considering the availability of detailed values of the operation and maintenance of a mechanical treatment unit from a study developed in the metropolitan region of Curitiba (South of Brazil) [25]. The initial investment value for a mechanical treatment plant to process 522 tons per day (Scenario A) is USD 6,408,007.88 and the investment to process 720 tons per day (Scenario B) is USD 8,838,631.58. Table 3 presents the cost of each unit for Scenario A and Scenario B, where Scenario A corresponds to 72.5% of the values of Scenario B.

Table 3. The installation costs of Scenarios A and B.

Unity	USD Scenario A (522 t/day)	USD Scenario B (720 t/day)
Mechanical treatment unit (grinding, rotary screen, air separator, metal separation, optical sensor, and final grinding)	4,250,737.06	5,863,085.60
Overhead crane	434,835.88	599,773.63
Overflow station	388,246.32	535,512.17
Road scale (30 tons)	52,426.47	72,312.37
Implementation lot	441,166.40	608,505.38
Infrastructure works (gate, access, water, sewage, and power connections)	79,577.88	109,762.59
Environmental compensation	116,097.84	160,134.95
Construction of the administrative support area	34,684.74	47,841.02
Design and construction of the shed that will house the mechanical treatment unit	513,573.53	708,377.28
Permanent stock of imported spare parts	23,294.12	32,129.82
Construction of a shed to stock the SRF produced	73,367.64	101,196.75

Source: Intermunicipal consortium for the management of urban solid waste [25].

For Scenario A, considering the sum of all AEC and the APSRF for a plant of 522 tons per day, it was possible to estimate that the cost per ton of SRF produced would be USD 6.77. For Scenario B, considering the sum of all AEC and the APSRF for a plant of 720 tons per day, each ton of SRF produced would cost USD 6.14. However, these estimations do not consider the logistical costs associated with sending the waste to the location of the plant and sending the produced SRF to the nearest cement plant. Nevertheless, the results suggest the economic feasibility of producing SRF, since the average value of a ton of petroleum coke, a fossil fuel widely used in the cement sector, was USD 220.00 as per the June 2021 values.

It is important to mention that a detailed cost analysis of the SRF production will require other factors to be analyzed, such as the composition of the waste, the market prices for petroleum coke, infrastructure for production, and distribution of SRF. For instance, the SRF market may become more or less attractive depending on the petroleum coke prices. Another determining factor for the production and use of SRF is its aforementioned benefits in terms of reducing atmospheric emissions and saving fossil raw materials.

4. Conclusions

SRF has emerged as a viable alternative for utilization in clinker production kilns, mainly due to the reduced availability of areas for landfill construction, the possibility of using materials with energy potential, and the sector's commitment to reduce atmospheric emissions. According to the results obtained herein, great heterogeneity of the samples that compose the rejected fraction from the WPC in Florianópolis was observed. It was estimated that, after removing the categories that can affect the quality of the SRF (clothes and shoes, organics, and glass and debris), 60.29% of the rejects from the WPC remained, representing the possibility of almost 118 tons per month to produce SRF.

One of the main factors cited in all legislation for the use of waste-to-energy purposes is a lower calorific value. In this study, an average net calorific value of 5429.66 kcal/kg was obtained, pointing out the attractiveness of the waste blend to produce SRF. In all WPC, the analyzed samples were composed of about 75.16% of plastics of different types. This directly affects the calorific value of the proposed SRF and indicates the rejected fraction from WPC as a good alternative to produce SRF. Furthermore, regarding chemical analyses, the proposed SRF has favorable characteristics for its production as it presented low levels of the parameters analyzed in comparison to other studies with a similar type of waste. When replacing petroleum coke with SRF for direct feeding into the clinker kiln, a decrease in the atmospheric emissions for all scenarios considered was achieved. Furthermore, considering two hypothetical SRF industrial plants with capacities of 522 and 720 t/day, each ton of SRF produced would cost about USD 6.00.

Accordingly, the results reported in this study suggest the energetic, environmental, and economic feasibility of using the rejected fraction from the WPC as raw material to produce SRF. However, it is important to emphasize that the production of SRF from MSW will require detailed studies to address the specificities of each scenario considered.

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