





Article

Reuse of Steel Residue in Polypropylene Matrices for the Production of Plastic Wood, Aiming at Decarbonization

Leticia S. Ribeiro ¹, Ana Lúcia Nazareth da Silva ^{1,2}, Mayara Amario ^{1,*} , Carina M. Stolz ¹ , Assed N. Haddad ¹ 
and Dieter Thomas Boer ^{3,*} 

¹ Programa de Pós Graduação em Engenharia Ambiental, Universidade Federal do Rio de Janeiro (PEA/UFRJ), Rio de Janeiro 21941-901, Brazil; leticiasimoes.pea20223@poli.ufrj.br (L.S.R.); ananazareth@ima.ufrj.br (A.L.N.d.S.); carinastolz@poli.ufrj.br (C.M.S.); assed@poli.ufrj.br (A.N.H.)

² Instituto de Macromoléculas Professora Eloisa Mano, Universidade Federal do Rio de Janeiro (IMA/UFRJ), Rio de Janeiro 21941-598, Brazil

³ Departament d'Enginyeria Mecànica, Universitat Rovira i Virgili, 43007 Tarragona, Spain

* Correspondence: mayara_amario@poli.ufrj.br (M.A.); dieter.boer@urv.cat (D.T.B.)

Abstract: According to a 2024 World Economic Forum survey, climate change is the primary concern for the future. To address these challenges, adaptation measures and actions to reduce or avoid greenhouse gas emissions are necessary. Emissions from the waste management sector rank as the seventh-largest contributor to global emissions. Efforts are underway to decarbonize steel processes and promote waste reuse. “Fluff”, generated during ferrous scrap processing, poses reuse challenges due to its characteristics. This study evaluates the production of wood–plastic composites using polypropylene and “Fluff” to address environmental concerns and reduce greenhouse gas emissions. Methodologically, waste characterization preceded the extrusion of waste and polypropylene blends at varying compositions. The resulting materials were pelletized, molded, and characterized. CO₂ emission reductions from waste diversion from landfills were assessed under two scenarios. In Scenario 1, emissions totaled 19,054 tons/year, while in Scenario 2, with gas capture and utilization, emissions reached 10,617 tons/year for 20,000 tons of waste annually. Composite characterization revealed favorable properties, suggesting viability for wood–plastic production. This approach supports industrial decarbonization and circular economy initiatives in the steel sector.

Keywords: Fluff; plastic wood; circular economy; steelmaking; decarbonization



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1. Introduction

Climate change is the primary concern for the future, according to a survey by the World Economic Forum. The World Economic Forum (WEF) publishes the Global Risk Report 2024, a report with the results of the Global Risks Perception Survey (GRPS), which considers the opinions of global leaders from academia, business, government, the international community, civil society, and experts in specific fields. The report describes the most severe global risks to economies and societies in the short term (2 years) and long term (10 years) to assist decision-makers (governments, entrepreneurs, etc.) in balancing current crises and long-term priorities. “Extreme weather events”, related to climate change and its consequences for terrestrial systems, are the second risk indicated for the next two years and the first indicated for the next 10 years [1].

The Intergovernmental Panel on Climate Change (IPCC) states that climate change is causing losses and damages to the planet and that climate-related natural disasters make people and ecosystems vulnerable. The increase in global temperature, a direct consequence of greenhouse gas emissions, raises the planet’s temperature and increases the frequency and intensity of extreme weather events. To deal with extreme weather events, adaptation measures to climate change are necessary, with actions to reduce or avoid greenhouse gas emissions [2].

The search for alternatives to reduce or eliminate greenhouse gas emissions in the production chain encompasses strategies such as reducing material demand through circular economy solutions, implementing carbon capture and storage technologies in challenging sectors, and transitioning to low-emission industrial processes. Actions aimed at the production of materials such as steel, cement, plastic, cellulose, paper, and chemicals are crucial in this context. Additionally, green guidelines for the construction and infrastructure sector, combined with energy standards for buildings and more sustainable materials, play a key role in promoting decarbonization [3].

China, the United States, India, the EU27, Russia, and Brazil were the six largest global greenhouse gas emitters in 2022. Emissions from the waste management sector are the seventh-largest contributor to global emissions. Global emissions related to waste in 2022 increased by 58% compared to 1990 [4]. The Waste Management segment assumes a significant position as the fourth largest emitter of greenhouse gases in Brazil, even surpassing Industrial Processes. Among the main emission sources in this sector, the final disposal of waste in landfills and other forms of disposal stands out, contributing to 34% of the total emissions from the waste segment [5]. In this context, to adopt decarbonization, it becomes essential to implement waste management strategies that avoid final disposal and incineration [6].

The steel industry is a significant generator of industrial waste globally, contributing to global environmental challenges. However, considerable efforts are being made to address this issue, with a particular focus on waste reuse as part of a broader decarbonization strategy. Despite significant advances in recent decades, including dramatic improvements in air emissions, water discharges, and waste disposal, there is still a long way to go in waste management [7].

Among the steel residues destined for landfills, the Fluff is generated in the processing stage of ferrous scrap (Figure 1). One of the most powerful pieces of equipment for scrap processing is the Shredder, composed of a mill equipped with a set of hammers, allowing efficient shredding of scrap into small, high-density pieces. Additionally, the Shredder is equipped with separation systems that remove non-ferrous material from the already shredded scrap, resulting in a final product not only of high density but also with a low concentration of non-ferrous metals. The scrap undergoes a magnetic separation stage, conducted by magnetic drums, which distinguish ferrous from non-ferrous parts. The resulting ferrous scrap is directed to the dedusting process and stored for use in furnaces. On the other hand, non-ferrous scrap may undergo a manual picking stage and be marketed, or, in certain steel mills, advance to the next phase in equipment known as the Eddy Current. In the Eddy Current, the scrap undergoes additional magnetic separation, proceeding to a vibrating chute where a conveyor belt directs the material to a magnetic inductor. In this inductor, contained residues such as plastics, rubbers, and foams are directed to an outlet, while non-ferrous metals are expelled by repulsion, contributing to an effective material separation process. The presence of impurities in the scrap can impair metal yield and complicate furnace operations, negatively impacting the quality of the produced steel. Thus, effective impurity removal reduces the likelihood of their fusion in the furnace, contributing to the decrease in energy consumption and the minimization of particulate matter generation [8,9].

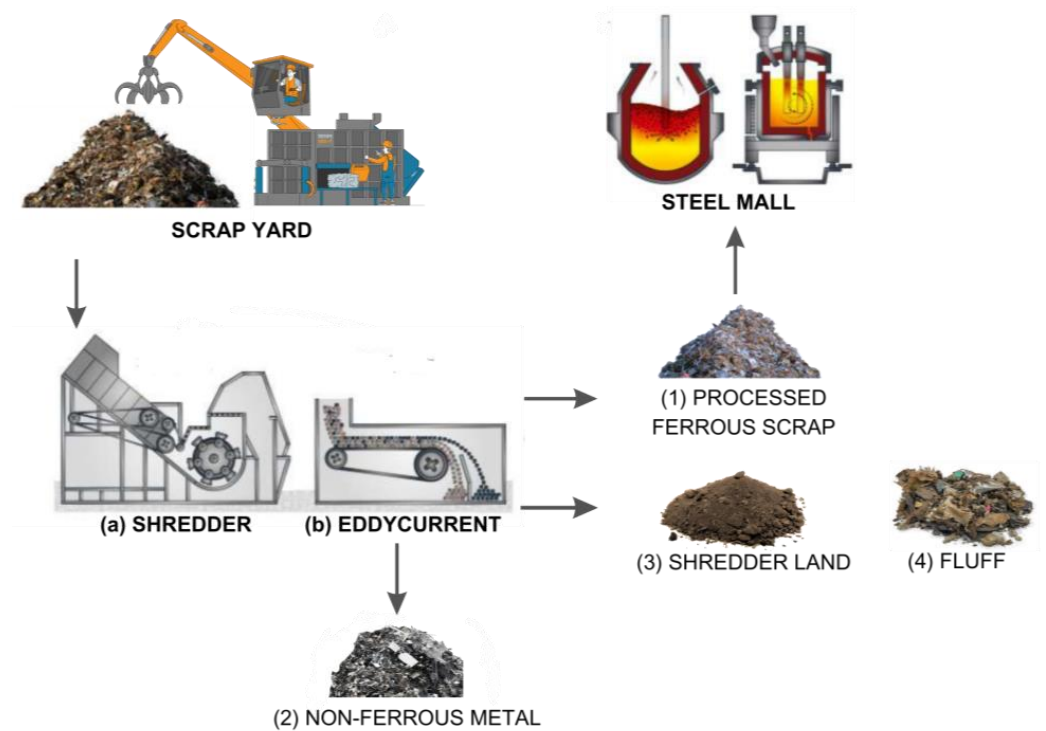


Figure 1. Generation scheme of waste in the Shredder equipment. Adapted from [10].

The ferrous scrap processed in the Shredder is directed to the Steelmaking Plant to be used as raw material in steel production. The impurities contained in the scrap are segregated into “impurities” and “non-ferrous metals”. Non-ferrous metals consist of copper, brass, aluminum, and others, and are easily marketed. The “impurities”, in some cases, are segregated into two parts, depending on the Shredder and the process implemented by the Steel Mill, often separated into “Shredder Dirt” and “Fluff”. The Dirt constitutes the fraction of higher density and smaller particle size, separated by particle size separation decks, containing a large amount of soil and fragmented volatile materials, with a smaller particle size compared to Fluff [7–11]. The Fluff is the material of larger particle size and lower density, with less soil content and a significant portion of volatiles, passing through the separation decks. These impurities, once segregated, need to be properly disposed of as process waste. The Fluff is a residue composed of a large amount of polymers and volatile materials, extremely heterogeneous, which complicates its sorting and recycling. Its use as fuel is often hindered by the presence of chlorine, which when burned, can result in the emission of dioxins and furans, substances harmful to health and the environment [6,12–14].

Given these issues, new alternatives for the utilization and sustainable disposal of these residues have been constantly sought. These residues do not have technically and economically viable applications and are destined for landfills [11,14–16].

In this context, new alternatives for the use and sustainable disposal of these residues have been constantly sought [8,15,17], since the disposal of this waste in landfills results in the emission of greenhouse gases [6,14]. A promising approach to utilize Fluff without the need for the sorting and separation of materials is to consider its incorporation into polymeric matrices for the production of wood–plastic composites. This strategy is particularly relevant because the construction industry, a major consumer of plastics, can play a crucial role in adopting more sustainable materials.

The incorporation of fillers into polymer matrices is a well-known application, where plastic or wood waste is typically incorporated into a known polymer matrix [18,19]. These composites find diverse applications across sectors such as construction, the furniture industry, transportation, technology, and others [20].

Several positive environmental impacts are attributed to the use of plastic waste in the production of wood plastic composites, as highlighted in the literature. The moderate incorporation of waste into wood plastic formulations is a practical and economical solution for recycling end-of-life products, especially plastics and fibers, resulting in the creation of high-performance composites [21], reducing waste and aligning with circular economy principles [22]. Moreover, replacing conventional wood with wood plastic can help reduce deforestation and the pressure on forest resources [23,24].

Given these advantages, the possibility arises to incorporate Fluff into polymer matrices for the production of wood plastic composites. Although there are studies on the incorporation of fibers and other wastes, no studies were found on the incorporation of Fluff into polymer matrices. This initiative could align with industry efforts toward decarbonization, helping to prevent greenhouse gas emissions associated with the final disposal of waste in landfills.

By exploring this alternative, the aim is to add value to Fluff and promote a circular economy by reintegrating these residues into the production chain, reducing dependence on virgin resources, and minimizing environmental impacts. This type of innovative and sustainable approach is essential to address current challenges related to waste management and climate change mitigation.

2. Materials and Methods

2.1. Sampling and Beneficiation of the Waste

The samples of the waste were provided by a Steel Mill located in Brazil. Due to the heterogeneity of the waste, caused by the wide variety of scrap entering the Shredder equipment, one of the main stages of the work, which directly influences the results, is the sampling process. Therefore, a sampling schedule was established to ensure that the sampling is as representative as possible and encompasses all types of scrap inserted into the Shredder equipment. The schedule consists of a period of 7 days, considering the collection of one sample per day, composed of waste from 3 points of the pile (bottom, middle, and top), as represented in Figure 2. At the end of the 7 days, the daily samples were homogenized and quartered, forming a single sample, according to the methodology established in NBR 10.007 [25], as represented in Figure 3.

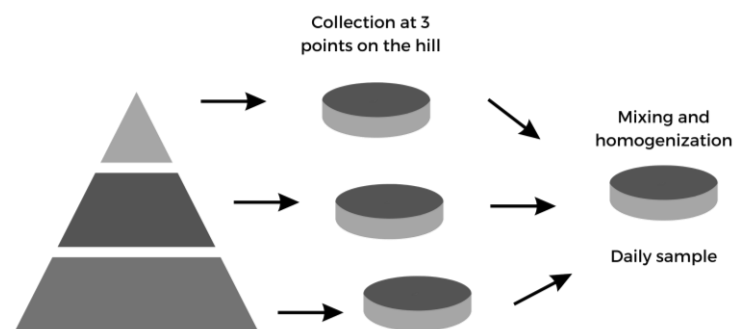


Figure 2. Daily collection at three points of the pile, forming a single sample.

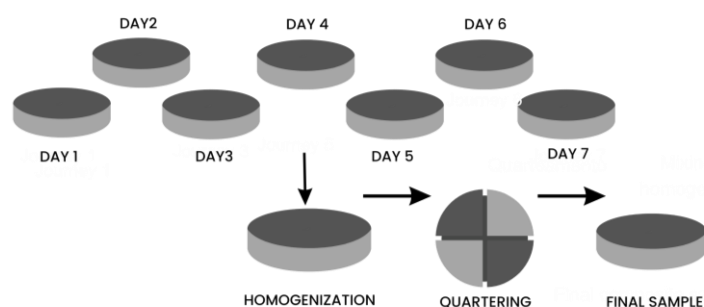


Figure 3. Homogenization and quartering of the 7 daily samples, producing a single sample.

2.2. Characterization of the Waste

2.2.1. Gravimetry

The materials were manually separated by handpicking and segregated into rigid plastics, flexible plastics, foams, Styrofoam, fabrics, rubbers, cardboard/paper, organics (wood pieces and branches), and metals (ferrous and non-ferrous) to obtain gravimetry.

2.2.2. Grinding

After gravimetry, the sample was disaggregated and ground in a knife mill from the Primotécnica brand, model LP 1003, using a mesh opening of 0.75 mm.

2.2.3. Thermal Behavior of the Waste

The thermal evaluation of the waste was obtained by thermogravimetry on a thermogravimetric analyzer (TGA), model Q500 from T.A. Instruments. The runs were obtained by heating the samples from 30 to 900 °C, at a heating rate of 10 °C/min.

2.2.4. Fourier-Transform Infrared Spectroscopy (FTIR)

Fourier-transform infrared spectroscopy (FTIR) was conducted using a germanium crystal, involving 64 scans, with a resolution of 4 cm⁻¹, to determine the structures present in the waste.

2.3. Composition Preparation

The polypropylene used in the study is from the brand Braskem, a multinational company located in São Paulo, Brazil. grade CP 442XP.

2.3.1. Preparation of the Compositions

The mixtures were prepared with 5% and 10% of Fluff and coded as R00—Neat-PP, R05—a mixture containing 95% of PP and 5% of Fluff, and R10—a mixture containing 90% of PP and 10% of Fluff (Table 1).

Table 1. PP/Fluff compositions.

Composition (PP/Fluff), % wt/wt	Code
100/0 (Neat-PP)	R00
95/5	R05
90/10	R10

Before extrusion, neat-PP (R00), R05, and R10 compositions were dried for 24 h in a forced-air oven at 60 °C.

2.3.2. Neat-PP and Composite Processing

The three compositions, neat-PP (R00), R05, and R10, were extruded in a co-rotating and interpenetrating twin-screw extruder, TeckTrill, model DCT-20 (L/D = 36, D = 20 mm), belonging to the Technological Support Laboratory (LAPTEC) at IMA/UFRJ. The temperature profile used varied from 90 to 200 °C, using a screw speed of 600 rpm. The screw profile used was suitable to ensure perfect dispersion of the waste in the plastic matrix. After extrusion, the prepared compositions were pelletized.

2.3.3. Compression Molding

The molding of the materials was performed using a hydraulic press with automatic cooling. For this stage, a metallic mold with dimensions of 10 × 10 × 0.3 cm was inserted between the press plates. These molds were adequately filled with the material pellets. The pressing temperature set was 210 °C. Once the plates were inserted into the press, the temperature was allowed to stabilize. Only then were forces of 2 tons applied and

maintained for 30 s. Then, a force of 10 tons was applied, which was sustained for 3 min. Between transitions, a pressure relief process, known as degassing, was implemented to minimize the formation of bubbles resulting from air entrapment in the samples. It is worth noting that this entire set of steps was repeated for each prepared composition.

2.4. Characterization of the Neat-PP and Composites

2.4.1. Thermal Properties of Neat-PP, R05, and R10 Compositions

The thermal stability of the three compositions was determined by thermogravimetry on a thermogravimetric analyzer (TGA), model Q500 from T.A. Instruments. The runs were obtained by heating the samples from 30 to 900 °C, at a heating rate of 10 °C/min. Differential scanning calorimetry (DSC) was performed in the temperature range from 30 to 250 °C at a heating rate of 10 °C/min.

The crystallinity degree of neat-PP and composites (R05 and R10) was obtained by using Equation (1) [26]. The $\Delta H_{100\%}$ is 207 J/g.

$$\chi_c = 100 \times \frac{\Delta H_f}{\Delta H_{100\%}} \quad (1)$$

2.4.2. Melt Flow Index (MFI)

The flow behavior of the neat-PP and composites (R05 and R10) was evaluated by the melt flow index (MFI). The analysis was performed on the DYNISCO equipment, model LMI 4000, following ASTM D1238-13 standard, using the properties defined in the standard for polypropylene (g/10 min, 230 °C, and 2.16 kg).

2.4.3. Tensile Properties

Tensile tests were performed on a universal testing machine EMIC DL-3000, Figure 4, using cell 24 and extensometer Trd 15. The test specimens were molded as established in ASTM D 638 standard, type V specimens.



Figure 4. Universal testing machine. EMIC DL-3000.

2.4.4. Fourier-Transform Infrared Spectroscopy (FTIR)

Fourier-transform infrared spectroscopy (FTIR) was conducted using a germanium crystal, involving 64 scans, with a resolution of 4 cm^{-1} , to determine the chemical groups present in the residue.

2.5. Calculation of Avoided Greenhouse Gas Emissions

To evaluate the avoided volume of greenhouse gas emissions by removing these waste materials from landfills and proposing their incorporation into composite materials for the production of wood–plastic products, a study was conducted addressing two distinct and empirical scenarios:

- Scenario 1: Disposal of waste in landfills without gas capture and utilization;
- Scenario 2: Disposal of waste in landfills with gas capture and utilization for energy generation.

To quantify these emissions, the “Greenhouse Gas Emission Calculation Tool (GEE) in the Management of Solid Waste in Brazil—Life Cycle Assessment (LCA) Methodology” was used, available for download on the Brazilian Government website, in the Ministry of Cities, adapting input data to the characteristics of the Fluff.

The calculator was chosen instead of using the GHG Protocol emission factor for waste disposal in landfills, as more accurate numbers based on the real composition of the waste were desired. The “Greenhouse Gas Emission Calculation Tool (GEE) in the Management of Solid Waste in Brazil” uses a specific methodology to calculate GEE emissions associated with the management of urban solid waste (RSU), including the disposal of steel waste in landfills. This tool was developed to provide detailed information for decision-making in different waste management scenarios.

The fundamental approach adopted by the calculator is the gas production theory, considered one of the simplest for estimating methane emissions related to waste management. This approach assumes that all methane generated from waste is released in the same year that the waste is generated. This premise is aligned with the Life Cycle Assessment (LCA) approach and differs from the guidelines of the IPCC, which uses a first-order decay model to account for temporal changes in methane production.

In the basic data entry stage of the tool, it is necessary to characterize the urban solid waste (RSU) that will be evaluated. This includes identifying the percentages of different materials present in the waste, such as organic waste, paper and cardboard, plastics, glass, ferrous metals, aluminum, textiles, rubber and leather, wood, mineral waste, and other materials. It is noted that the expected composition for RSU resembles the composition found for “Fluff”, and therefore, basic input data were related to Fluff gravimetry [27].

For emission calculations, factors influencing emissions were considered, such as waste volume, emission factors, gas capture by the landfill, and whether there is energy generation at the landfill and its oxidation layer:

- For the calculations, an annual waste disposal volume of 20,000 tons was utilized. Emission Factors: The emission factors assumed in the calculator consider that 50% of the organic carbon in the waste decomposes into landfill biogas over the landfill’s lifespan. This decomposition rate is higher in landfills than in anaerobic biodigestion processes due to the longer degradation period. Additionally, it is assumed that 55% of the decomposed organic carbon converts to methane, while 45% converts to biogenic CO_2 , which is considered climate-neutral [27];
- Gas Capture: The efficiency of gas collection is crucial for calculating GHG emissions from the final disposal of waste. Effective gas capture and utilization reduce fuel consumption and enter the mass balance. Gas collection efficiency rates in landfill recovery projects vary widely, from 9% to over 90%. However, it is estimated that, over the landfill’s entire lifespan, only half of the potentially generated methane can be captured, even with advanced gas collection techniques. The average gas collection efficiency used for these calculations was 50% [27];

- **Energy Generation:** Generating electricity from landfill gas significantly reduces methane emissions. Additionally, this approach offers extra benefits, such as replacing conventional energy sources like the average Brazilian grid electricity. The calculator assumes a methane energy content of 10 kWh/m³. Avoided GHG emissions for electricity are calculated based on a GHG emission rate of 338 g CO₂-eq./kWh for the replaced diesel [27];
- **Landfill Oxidation Layer:** Concerning the oxidation layer, which reflects the amount of CH₄ oxidized in a landfill soil cover or other cover material when properly managed, an oxidation factor of 0.1 is used to estimate methane oxidation during its diffusion through the top layer and through openings and fissures. Therefore, an oxidation factor of 10%, as suggested by the Greenhouse Gas Emission Calculation Tool (GEE) methodology in the Management of Solid Waste in Brazil, was adapted [27].

3. Results and Discussions

3.1. Waste Characterization

After homogenization and quartering, a separation method of materials was applied through manual gravimetric analysis, making it possible to determine the percentage composition of the different materials present in the waste. The values obtained indicate that the waste is composed of Rigid Plastics (28%), Flexible Plastic (14%), Foams (7%), Styrofoam (1%), Fabrics (9%), Metals (13%), Cardboard/Paper (3%), Organics (7%), Rubber (15%), and a fraction of difficult separation, composed of small unidentified fragments and soil (5%), as illustrated in Figure 5. This quantitative analysis provides information for the proper management and implementation of effective treatment and disposal strategies for the different types of materials present in the waste.

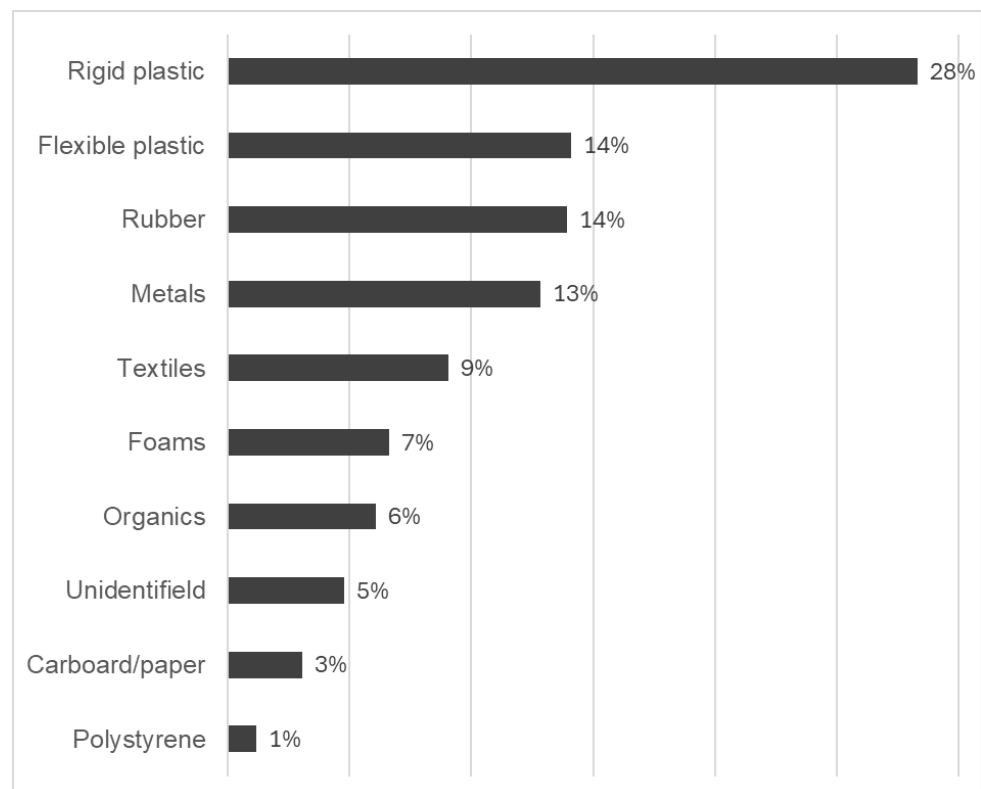


Figure 5. Results of waste gravimetry, in percentage.

The listed materials exhibit a diversity of compositions, with some of them classified as polymers (Figure 6).



Figure 6. Materials separated during gravimetry.

After gravimetry, the metals were discarded, and the remaining materials were mixed again to proceed to the subsequent steps.

3.1.1. Thermogravimetric Analysis (TGA)

The TGA/DTG curves (Figure 7) indicate that the Fluff residue contains different compounds with distinct molar masses, coinciding with the results obtained in gravimetry, which show various components. Among these components, we observe that plastics, rubbers, organic materials, and metals have different decomposition temperatures, as can be seen in the figure.

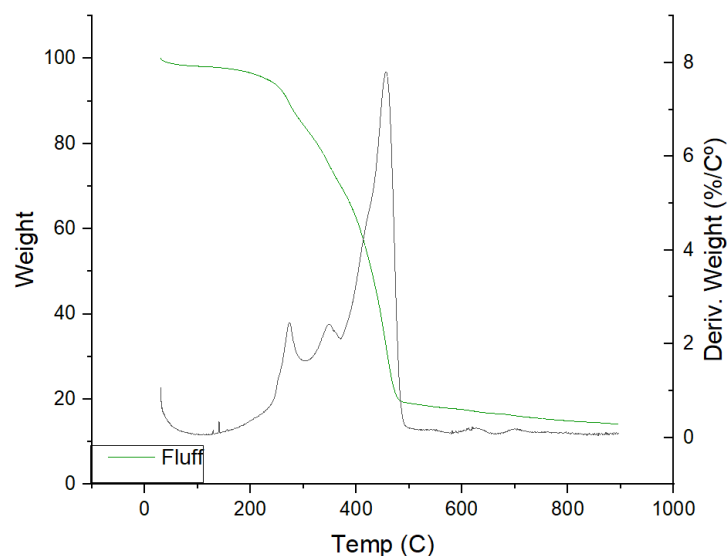


Figure 7. TGA/DTG curves of Fluff residue.

Each compound has different degradation ranges, signaling the complex composition of the analyzed residue. For instance, the initial degradation temperature (T_{ONSET}) of the Fluff sample was measured at 205 °C, while the temperature at maximum degradation rate (T_{MAX}) was observed at 455 °C, with a remaining residue of 14% (Table 2). The results are similar to those found in [11].

Table 2. TGA/DTG curves for the Fluff.

Sample	Initial Degradation Temperature (T_{ONSET}) (°C)	Temperature at Maximum Degradation Rate (T_{MAX}) (°C)	Residue (%)
Fluff	205	455	14

3.1.2. Fourier-Transform Infrared Spectroscopy (FTIR) Analysis

Fourier-Transform Infrared Spectroscopy (FTIR) analysis is a tool for identifying functional groups in various chemical compounds. By absorbing infrared radiation, FTIR allows for the identification of specific chemical bonds present in organic and inorganic molecules. For the Fluff residue, both organic and inorganic compounds can be observed (Figure 8).

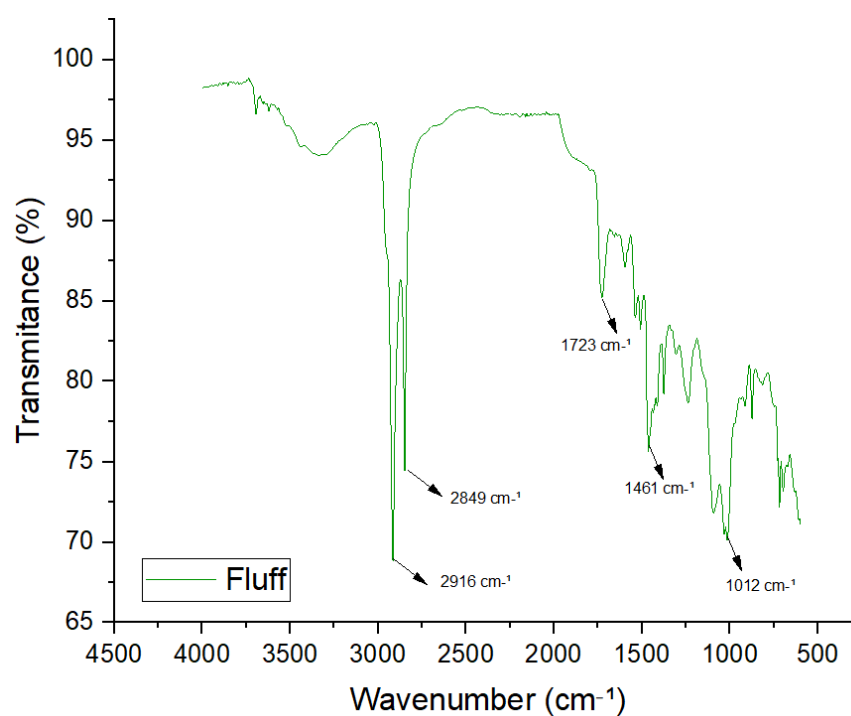


Figure 8. FTIR spectrum of Fluff residue.

The peaks at 2916 cm^{-1} and 2849 cm^{-1} are related to asymmetric C-H bonds, commonly found in hydrocarbons present in plastics, rubbers, and other polymeric materials. Peaks at 1723 cm^{-1} and 1596 cm^{-1} indicate C=O bonds, characterizing carbonyl groups common in organic compounds such as aldehydes and ketones, present in plastics and other polymeric materials. The peak at 1463 cm^{-1} is attributed to C-H bonds in methyl groups, found in polymers like polyethylene and polypropylene. Additionally, the peak at 1376 cm^{-1} may be associated with C-H bonds in methyl groups, while the peak at 1237 cm^{-1} suggests the presence of C-O bonds, found in ethers and alcohols present in plastics and organic materials. Peaks at 1093 cm^{-1} and 1016 cm^{-1} indicate C-O bonds, common in alcohol and ether groups. Finally, peaks below 1016 cm^{-1} are associated with C-H bonds in aromatic rings and aliphatic chains, suggesting the presence of polymeric and organic materials [28,29]. The results are displayed in Table 3.

Table 3. FTIR results for Fluff residue.

Sample	Peak (cm ⁻¹)	Bond	Suggested Group	Suggested Material
Fluff	2916 and 2849	C-H	Hydrocarbons	Plastics, rubbers, and other polymeric materials
	1723 and 1596	C=O	Carbonyl	Plastics and other polymeric materials
	1462	C-H	Methyl	Polymers such as polyethylene and polypropylene
	1237	C-O	Ethers and alcohols	Plastics and organic materials
	1016	C-H	Aromatic rings and aliphatic chains	Polymeric and organic materials

3.2. Neat-PP and Composite Processing

The residue was ground, and it was observed that after grinding, the sample formed clumps due to the foam present being fragmented into smaller pieces. It is also noted that some rubbers were not fragmented by the mill, remaining intact. Despite these characteristics, there were no difficulties in the process of feeding the material into the extruder.

During the extrusion process, it was observed that the R05 mixture, containing 5% residue, resulted in a more uniform and rigid filament. On the other hand, the R10 mixture, with an addition of 10% of residue, produced a filament with variations in its thickness, presenting thicker and thinner areas, signaling heterogeneity in the dispersion of the residue in the polymeric matrix. Meanwhile, the R00 mixture (neat-PP) generated a filament of uniform thickness but thinner compared to the other materials (Figure 9), as expected.

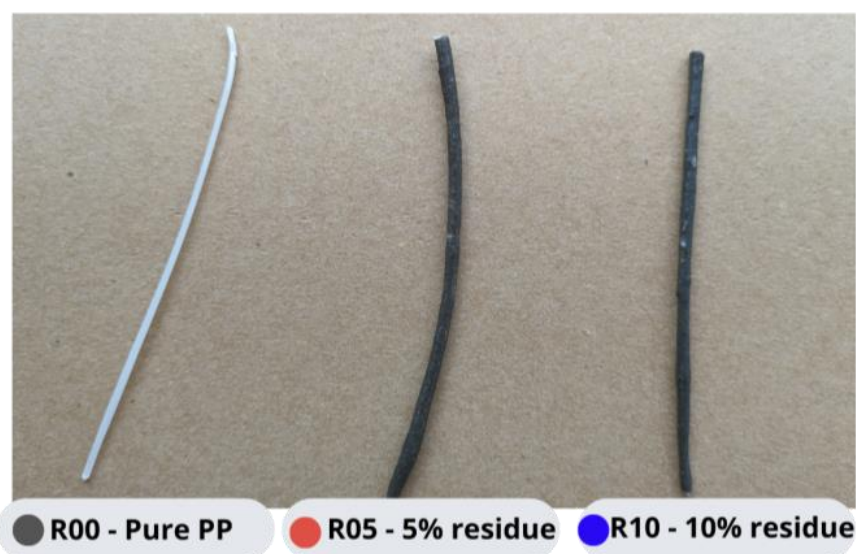


Figure 9. Monofilaments obtained by extrusion of materials R00 (neat-PP), R05 (PP + 5% Fluff), and R10 (PP + 10% Fluff) (% wt.).

3.2.1. Granulation Process of Extruded Materials—Pelletization

During the granulation stage of the filaments, it was observed that the R05 composite, containing 5% (% wt.) of residue, resulted in pellets with uniform coloring and a consistent dark brown hue. In contrast, the R10 composite, with 10% (% wt.) of added residue, exhibited a less homogeneous coloration, showing areas with a more whitish tone, which may indicate non-uniform dispersion of the residue in the PP matrix. As for the R00 filament, composed exclusively of pure PP, pelletization resulted in pellets with finer dimensions and typical PP granule characteristics (Figure 10).



Figure 10. Pellets obtained after extrusion and pelletization of materials R00 (PP), R05 (PP + 5% Fluff), and R10 (PP + 10% Fluff) (% wt.).

3.2.2. Compression Molding

The pellets were molded by compressing to obtain a uniform plate. Figure 11 shows the plates produced from each sample through compression molding.

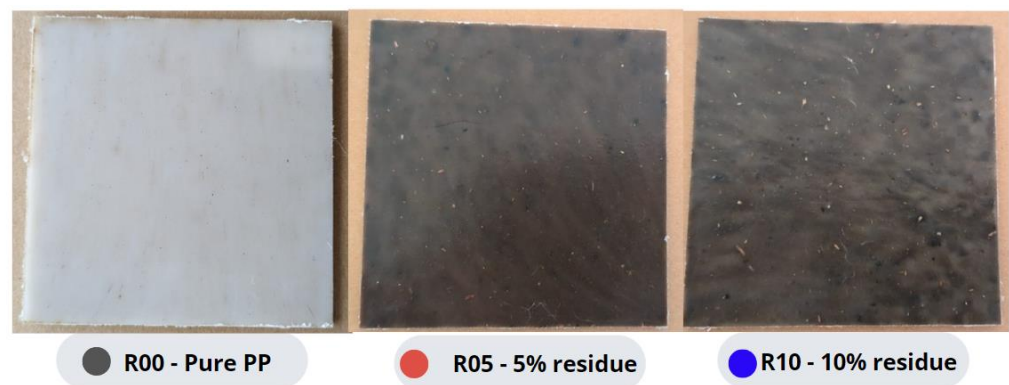


Figure 11. Composites R00 (PP), R05 (PP+5% Fluff), and R10 (PP+10% Fluff) (% wt.).

As can be observed, the materials still exhibit visible fragments, with the R10 sample, with 10% residue addition, showing less uniformity in terms of color compared to the R05 sample, with 5% residue addition.

It can be noted that the produced composites exhibit a noticeable visual resemblance to wood–plastic, both in terms of structure and coloration.

It is noted that the natural coloration of the plates was brown (Figure 11), without the need to add any additive to enhance the wood-like appearance. The visible fragments gave a visual aspect of sawdust, very similar to conventional wood–plastic, produced with plastic and sawdust.

3.3. Characterization of the Neat-PP and Composites

3.3.1. Melt Flow Index (MFI)

The MFI analysis evaluated the flow behavior of the compositions R00, R05, and R10, and the results are shown in Table 4.

Table 4. Melt flow index (MFI) results for the neat-PP (R00), R05, and R10 composites.

Composition PP/Fluff	Melt Flow Index (g/10 min)
R00	3.42 ± 0.005
R05	3.26 ± 0.006
R10	3.12 ± 0.009

From the results, it is observed that the MFI values tend to decrease with the increase in Fluff content (around 5%—R05 and 10%—R10, about R00), signaling that as the residue is added, the flow of polymer chains is hindered, resulting in a viscosity increase. This occurrence has been evidenced by other authors, who observed a reduction in flow indices with the addition of fillers in polymeric matrices. This suggests that, upon incorporating fillers, viscosity tends to increase. This phenomenon is commonly observed in composite materials, where the presence of additional particles interferes with the flow of polymer chains, resulting in increased flow resistance and, consequently, a reduction in material fluidity [30,31].

3.3.2. Thermogravimetric Analysis (TGA)

Table 5 shows the TGA results for neat-PP (R00) and composites R05 and R10.

Table 5. TGA results for R00, R05, and R10 compositions.

Sample	Initial Degradation Temperature (T_{ONSET}) (°C)	Temperature at Maximum Degradation Rate (T_{MAX}) (°C)	Residue (%)
R00 (PP)	268	434	0.05
R05 (PP + 5%)	270	452	0.23
R10 (PP + 10%)	270	457	1.63

The data from Table 5 show that the addition of Fluff to the PP matrix led to an increase in T_{MAX} values, maintaining the T_{ONSET} temperatures, signaling that there is a good interaction between Fluff and PP phases. As expected, as Fluff is added, an increase in residue values occurs, indicating materials with higher degradation temperatures that were not completely degraded.

In summary, the TGA results indicate that the incorporation of steel waste in the preparation of polymeric composites did not negatively impact the thermal stability of the materials. Composites R05 and R10 showed slightly higher temperatures at maximum degradation rate (T_{MAX}) compared to neat-PP (R00).

3.3.3. Differential Scanning Calorimetry (DSC) Analysis

The differential scanning calorimetry (DSC) analysis showed that R00 (neat-PP) exhibited a melting temperature (T_m) of 119 °C, while composites R05 and R10, with 5% and 10% (% wt.) contents, showed slightly higher temperatures, increasing by 5.54% for R05 and 6.21% for R10. This suggests a trend of increasing the crystallinity of the material with the addition of the Fluff residue. However, the crystallization temperatures (T_c) for composites R05 and R10, with 5% and 10% contents, are practically similar to that of neat-PP, indicating that the addition of the residue did not significantly affect this property.

The variation in fusion enthalpy (ΔH_f), which represents the enthalpy required to melt the material, increased in the composites compared to R00, an increase of 5.00% for R05 and 8.40% for R10, as shown in Table 6. This suggests that the addition of the residue contributes to a greater amount of energy required to melt the material, possibly due to a stronger interaction between the phases. Such behavior led to an increase in the crystallinity degree of the composites.

Table 6. DSC results for neat-PP (R00), R05, and R10 compositions.

Sample	Melting Temperature (T_m) (°C)	Crystallization Temperature (T_c) (°C)	ΔH_f (J/g)	Crystallinity Degree (χ_c) (%)
R00 (PP)	119	155	105.80	51
R05 (PP + 5%)	126	154	111.10	54
R10 (PP + 10%)	127	155	114.70	55

3.3.4. FTIR Analysis

Based on the results of the FTIR analysis of the R00, R05, and R10 compositions, no emergence of new peaks or significant shifts in the initial positions of the wavelengths were identified compared to R00.

The lack of emergence of new peaks or significant shifts in the positions of the wavelengths in the FTIR analysis between the R00 composite (composed of neat-PP), R05, and R10 may indicate that the chemical structure of the materials remained relatively stable after the addition of the residue.

This suggests that the addition of Fluff did not result in structural changes that substantially altered the characteristics observed in the FTIR spectrum of PP. This stability in the chemical structure is important as it indicates that the molecular integrity of the material was not compromised by the addition of the residue (Figure 12).

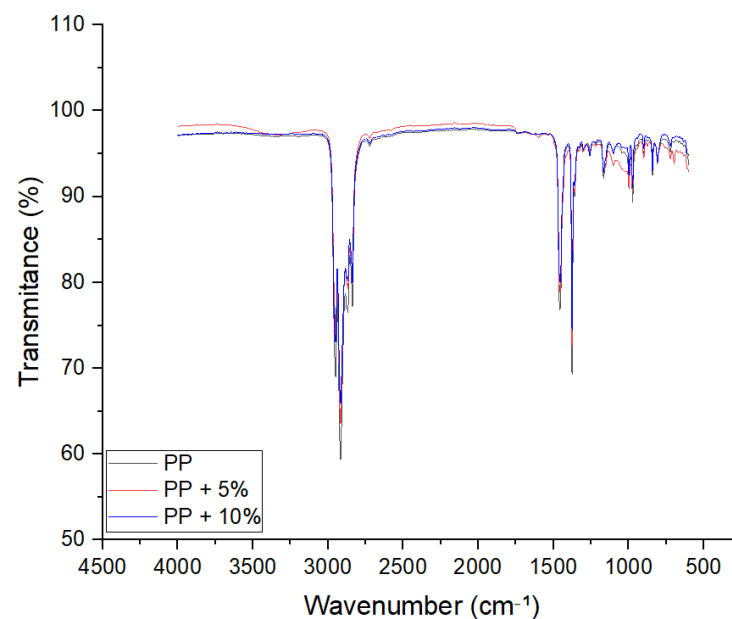


Figure 12. FTIR spectra of R00 (neat-PP), R05, and R10 composites.

3.3.5. Tensile Properties

The molded and pressed butterfly-shaped specimens (Figure 13) were subjected to tensile testing.



Figure 13. Specimens of the molded and pressed composite samples in butterfly shape.

The tensile properties of the composites are presented in Table 7, where Young's modulus is associated with the material's stiffness, representing its ability to resist elastic deformation under tension. The results obtained were similar to those presented by other authors who incorporated fibers into polypropylene matrices and experienced variations in the strength results due to the addition of fillers [32,33].

Table 7. Results of the tensile test for the composites.

Composite	Young's Modulus (MPa)	Stress at Break (MPa)	Strain at Break (%)
R00 (PP)	1082 ± 213	19.85 ± 1.63	14.69 ± 3.66
R05 (PP + 5%)	1058 ± 227	18.96 ± 2.86	11.43 ± 2.65
R10 (PP + 10%)	1087 ± 233	20.63 ± 1.28	15.29 ± 4.17

It is observed that Young's modulus of all compositions remained close to that of neat-PP, and the strain at break for R05 (PP + 5% Fluff) showed a slight reduction, which can be disregarded considering experimental errors. This suggests that the stiffness of polypropylene was not significantly altered with the addition of the Fluff residue.

Regarding the properties of stress at break and strain at break, the values are also similar between the compositions.

The tensile property results show that the addition of Fluff residue did not alter the mechanical integrity of neat-PP, indicating the preservation of the fundamental structural properties of the polypropylene.

3.4. Calculation of Avoided GHG Emissions through Application

In the two proposed scenarios, it is observed that greenhouse gas emissions from the disposal of 20,000 tons of steel waste in landfills are significantly high. In Scenario 1, which represents the disposal of waste in landfills without gas recovery, emissions total 19,054 tons of CO₂eq per year. Meanwhile, in Scenario 2, where waste is directed to landfills with gas capture and utilization for energy generation, a notable reduction in emissions is recorded, totaling 10,617 tons of CO₂eq per year.

In this context, the incorporation of waste into wood–plastic-based construction materials emerges as an effective strategy to significantly reduce these emissions and promote more sustainable waste management practices.

4. Conclusions

The sampling methodology proved to be crucial in obtaining an accurate representation of the residue, given its heterogeneity. Gravimetric analysis revealed that the residue is mainly composed of Rigid Plastics (28%), Flexible Plastics (14%), Rubber (14%), Metals (13%), Foams (7%), Textiles (9%), Cardboard/Paper (3%), Organics (6%), Not identified (5%), and Polystyrene (1%). Thermogravimetric (TGA) and FTIR analyses confirmed the presence of a variety of organic and inorganic compounds.

During the grinding process, clumps were formed due to the fragmentation of foams into smaller pieces. Some rubbers were not fragmented by the mill, remaining intact. In the extrusion stage, it was noted that the R05 composite, with 5% residue, resulted in a more uniform and rigid filament compared to R10, which contained 10% residue. In the granulation of the filaments, R05 presented pellets with uniform coloration, while R10 exhibited less homogeneous coloration, suggesting uneven dispersion of the residue in the PP matrix. The color of the plates was naturally brown, resembling conventional plastic wood.

Thermogravimetric (TGA) analyses indicated that the incorporation of the Fluff residue did not negatively affect the thermal stability of the materials. Differential scanning calorimetry (DSC) showed a slight increase in melting temperatures in the composites, suggesting an increase in the crystallinity of the composite with the addition of the residue. FTIR analysis revealed stability in the chemical structure of the materials after the addition

of the load. The melt flow index decreased with the addition of the residue, while tensile tests indicated that the mechanical integrity was maintained.

The calculation of greenhouse gas emissions, for the two proposed scenarios, indicated that reusing the residue as raw material instead of being sent for final disposal in landfills is an important strategy for decarbonization in the Steel Industries. In Scenario 1, emissions totaled 19 thousand tons of CO₂eq per year, while in Scenario 2, with gas utilization, 10 thousand tons of CO₂eq per year were recorded for the final disposal of 20 thousand tons of residues annually.

With the results obtained, it is concluded that the reuse of Fluff residue in polymeric matrices to produce plastic wood is feasible and can be an important tool to support steel industries in the decarbonization process of their activities. Opportunities for future work include the use of PCR-PP or other post-consumer polymers, increasing the product's sustainability. Additionally, the use of an industrial-scale extruder for testing with a higher percentage of Fluff would be beneficial. However, despite being a durable product designed to last for years, it would be interesting to assess the recyclability of plastic wood containing Fluff.

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