CIRCULAR ECONOMY IN ADDITIVE MANUFACTURING: CARBON FOOTPRINT AND PERFORMANCE OF RECYCLED PP PARTS FABRICATED BY FFF ACCORDING TO ISO 14067

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Abstract:
This study evaluates the technical and carbon footprint performance of recycled polypropylene (rPP) for fused filament fabrication (FFF) under ISO 14067 cradle-to-gate boundaries, triangulating evidence with life cycle and mechanical data (1.95-1,84 kg CO_2-eq/kg). A systematic screening across Scopus, Web of Science, and journal portals (Polymers and Sustainability) applied five filters on 25 findings, 13 met all inclusion criteria and were retained for qualitative synthesis. Using the measured process energy demand for filament production and the Brazilian grid factor for the carbon footprint comparing with virgin resin production, the literature indicates rPP may average ~0.53 kg CO_2-eq/kg, implying an absolute decrease of 1.43-1.31 kg CO_2-eq/kg relative to virgin PP under comparable scope and assumptions. In addition, mechanically, evidence shows rPP parts can achieve application-viable performance when FFF parameters are properly controlled. The polymer chemistry retains 0.857 kg of carbon per kilogram (≈3.14 kg CO_2-eq "stored"), reinforcing circular-economy benefits by preserving solid-phase carbon and lowering emissions. Overall, the results support adopting rPP in FFF to deliver functional components with a demonstrably lower carbon footprint.

Keywords: Recycled Polypropylene (rPP), Fused Filament Fabrication (FFF), Additive Manufacturing, Circular Economy, Sustainable Materials

Abbreviations: AM, Additive Manufacturing. FFF, Fused Filament Fabrication. PP, Polypropylene. rPP, Recycled Polypropylene. LCA, Life Cycle Assessment. CF, Carbon Footprint. CO_2, Carbon Dioxide. CO_2-eq, Carbon Dioxide Equivalent. CE, Energy Consumption. EF, Emission Factor.

1. Introduction

The exponential growth in plastic waste poses significant challenges to traditional linear production models, which are characterized by extraction, production, consumption, and disposal. Circular economy emerges as a paradigm capable of promoting efficient material management, aiming to minimize environmental impacts and maximize resource value throughout their life cycle [1] [2].

When applied to polymers, this strategy emphasizes the reuse and recycling of thermoplastic materials, reducing the demand for fossil-based plastic production while mitigating greenhouse gas emissions.

Additive manufacturing, particularly the Fused Filament Fabrication, presents itself as a promising technology for the integration of recycled plastic waste into new products. By directly transforming filament made from recycled polypropylene into functional parts or products, FFF helps close the production loop for plastics, thereby enhancing circularity in the 3D printing sector [3].

Furthermore, the flexibility of processing parameters offers opportunities for the simultaneous optimization of mechanical performance and sustainability.

Despite the growing interest in **rPP** for 3D printing, systematic studies correlating the mechanical properties of prints produced from **rPP** and its carbon footprint impact remain limited.

Previous investigations have shown the technical feasibility of using **rPP** after multiple recycling cycles, while retaining strength and stiffness properties close to those of virgin material, as well as significant reductions in **CO_2** emissions [3] [5].

However, methodological gaps persist regarding the integration of these findings into a unified framework to support decision-making of circular economy-oriented public policies.

The present work proposes a systematic review that articulates mechanical characterization and life cycle assessment (**LCA**) for **rPP**-based products via **FFF**. By aligning operational parameters with the normative requirements of **ISO 14067** this study aims to provide robust guidelines for the development of sustainable additive manufacturing of **rPP**, thereby strengthening the incorporation of circular economy principles into industrial and academic processes, and political recycling polices [6].

2. Methodology

Initially, to conduct this study, a search was performed in five renowned databases: **Scopus**, **Web of Science**, **ScienceDirect**, **Polymers** (Web of Science Core Collection) and **Sustainability** (Scopus).

Using a preliminary list of 25 publications on **AM** with recycled polymers. Five sequential filters were applied:

(1) Publication period between 2015 and 2025.

(2) Language (English and Portuguese).

(3) Document type (research articles, systematic reviews and official sources).

(4) Thematic relevance (**FFF** printing of recycled polypropylene or life cycle analysis).

(5) Minimum methodological quality (presence of quantitative standardized data).

Consequently, of the **25** records screened for this article under the imposed criteria, **4** were published outside the predefined timeframe, **2** failed the document-type criterion, **3** did not report **LCA** data, and **3** lacked standardized experimental protocols; therefore, **13** studies met all inclusion criteria and were retained for qualitative synthesis and potential meta-analysis. This procedure ensures transparency, reproducibility and adherence to international systematic review standards, thereby establishing the rigorous methodological foundation that precedes the exposition of this work's central problem.

2.1. Carbon Emissions

Carbon footprint is defined as the sum of all greenhouse gas emissions (expressed in kg **CO_2-eq**) generated over the life cycle of a product or process, within a defined scope—in this case, from the fabrication of **PP** filament to its use in **AM**.

The **CF** comprises emissions from raw material production (virgin **PP**) and from the processing required to convert that polymer into printing filament.

In **2022**, global **CO_2** emissions reached **36 Gt**, of which approximately **4%** are attributed to the production of polymers for additive manufacturing. In that same year, worldwide polypropylene (virgin **PP**) production totalled **79 Mt**, with an average carbon footprint of **1,95 kg CO_2-eq** per kilogram of material [4].

In Brazil, total plastic consumption in **2023** was **7 Mt**, of which about **20%** (**1.4 Mt**) was **PP**. However, only **25,6%** of that **PP** (**≈360 kt**) was recycled, meaning approximately **1,04 Mt** of virgin PP ended up in landfills. [4] [10].

2.2. Recycling Machinery

We adopt a compact filament production line composed of a **Filmaq3D** CV extruder, an **FTR1** puller/cooler, and an **FE1** winder. To quantify the carbon footprint of recycled polypropylene (**rPP**) filament production, this section specifies the extrusion machinery that converts **rPP** into printable spools, because equipment configuration and duty cycle determine the specific electricity demand per kilogram [9].

With a suitable extruder for reprocessing recycled polypropylene into filament, it is characterized the electrical consumption of the **Filmaq 3D** system used in this study, adopting the power ratings provided by the manufacturer. The extruder operates between ≈ **500–600 W**, varying with temperature and rotation speed; the **FTR1** consumes ≈**60 W**, depending on pulling speeds and fan operation; and the **FE1** consumes ≈**30 W**, according to the motor speed. Combined, the three units require approximately **690 W** during joint operation, resulting in **350g** of filament per hour [9].

This aligns with the experimental setups used in the referenced study, particularly for the mechanical testing and extrusion reproducibility [3] [4] [8].

2.3. Carbon Footprint

According to **ISO 14067:2018**, the carbon footprint must account for emissions across the product's life cycle. The Brazilian average emission factor for electricity generation is **0,0289 kg CO_2/kWh** [7].

The energy consumption of the extrusion process, from producing each kilogram of **rPP** was measured at:

$$(0.69\ \mathbf{kW}) / (0.35\ \mathbf{kg{\cdot}h^{-1}}) = 69/35\ \mathbf{kWh/kg}$$
$$\approx \mathbf{1{,}9714\ kWh/kg}$$

The resulting emission from energy use is calculated as follows:

$$\mathbf{CF}_{energy} = \mathbf{CE} \times \mathbf{EF} \qquad (1)$$

CE: energy consumption per kg

EF: emission factor

CF_{energy}: energy-related carbon footprint

Thus, the total **CF** of the filament is:

$$\approx \mathbf{0{,}0569\ kg\ CO_2/kg}$$

This value represents the contribution of energy use to the total carbon footprint of the filament. To quantify the **CF** of virgin **PP** filament, we adopt between **1,95–1,84 kg CO_2-eq/kg** given different polymer production lines, while applying **ISO 14067** cradle-to-gate boundaries and the measurement requirements [11][12].

In comparison **rPP**, from post-consumer polypropylene recovered after product use, collected in municipal streams, then sorted, washed, and mechanically re-granulated into pellets, averages **0,53 kg CO_2-eq·kg^{-1}**, yielding an absolute reduction of around **1,42-1,31 kg CO_2-eq·kg^{-1}** and a relative improvement by simply selecting **PP** from recycled origin of, approximately, **27-32%**, when compared to the virgin filament alone. [12].

This benefit is achieved while retaining **0,857 kg of fixed carbon** per kilogram of polymer—equivalent to **3,14 kg CO_2-eq**—chemically "stored" in the **PP** chain.

2.4. Quantifying Carbon Storage

Table 1 shows the chemically "stored" carbon in 1 kg of virgin **PP**, corresponding to the molar fraction of carbon (C_3H_6) in the polymer chain. Followed by the calculations that led to the metric.

Table 1. Carbon "recovered" in recycled **PP**

Parameter	Kg of Virgin PP
Fixed carbon (kg C/kg)	0, 857
"Stored" (kg CO_2-eq)	3, 14

By fixing **0,857 kg CO_2-eq /kg** of material, **PP** retains the equivalent of **3,14 kg CO_2-eq**, according to the stoichiometric relation between carbon and carbon dioxide [6].

Equation (2) calculates the **mass fraction of carbon** (Cf) in 1 kg of polypropylene (**PP**), based on the stoichiometric composition of its repeating unit (C3 H6).

$$C_f = \frac{n_C \cdot M_C}{M_{C_3H_6}} \tag{2}$$

The molar mass of **CO_2** is **44,01 g/mol**, while the molar mass of carbon is **12,01 g/mol**. The ratio (M_{CO2}/M_C) represents the mass of **CO_2** produced per unit mass of carbon oxidized.

$$CO_{2eq} = 0.857 \times \frac{44.01}{12.01} = 3.14 \text{ kg } CO_2\text{-eq/kg PP}$$

This value represents the amount of **CO_2** chemically "stored" in the polymer's molecular structure.

Within the framework of a circular economy, mechanical recycling of **PP** preserves this carbon in the solid phase, preventing its conversion to atmospheric **CO_2** and thereby contributing to climate-change mitigation.

The accurate **CF** combines emissions from polymer production and the energy-related component calculated above:

CF Total = **CF** Production + **CF** Energy (3)

However, when the polypropylene is being recycled, the **CF** inherited of its production is not readded to this measurement, leaving only the **CF** from the energy used to manufacture the recycled product.

Therefore, the ratio between **CF** from the production and **CF** from the energy used to recycled **PP** gives the percentage improvement from using **rPP** when compared to **PP**.

$$\% = \text{CF Energy} / \text{CF Production} \quad (4)$$

Now, the impact of using **o**n the **CF** between the production, and later consumption, of **rPP** when compared to the production of virgin **PP** solely for additive manufacturing is of around **97,08%**, by using the setup line of filament production described (**Fimaq3D**).

Interpreting this value underpins the circular economy analysis: when the polymer is recycled, this carbon reservoir is preserved, preventing its re-oxidation.

3. Conclusion

These results support using **rPP** in additive manufacturing to produce parts with mechanical performance similar to virgin **PP** but with a lower carbon footprint, when compared to the production of more filament instead of repurposed **PP**.

Applying **ISO 14067** cradle-to-gate boundaries and the measured process energy, the energy-related footprint of filament extrusion (With **Filmaq3D** production line) is:

$$CF_{energy} = 0{,}05697 \text{ kg } CO2/kg$$

Using the Brazilian grid factor to measure the **CF** from the energy used to repurpose the polymer (Making **rPP** filament) and correlating with the **CF** from the production of virgin filament (**1,95-1,84 kg CO2-eq/kg**), when comparing to that of recycled origin yields approximately **21,54%** diminish in the **CF**, for additive manufacturing purpose, under the presented operating profile [7][11].

In parallel, the polymer retains **0,857 kg C/kg** (**≈ 3,14 kg CO2-eq/kg**) chemically stored in the **PP** chain, reinforcing the circular-economy rationale that mechanical recycling preserves carbon in the solid phase and avoids re-oxidation to atmospheric **CO^2** [1][6].

According to **ISO 14067:2018**, accounting for emissions across the entire product's life cycle, the **CF** of **rPP** beginning at **0,53 kg CO2-eq/kg** with increases of **0,05697 kg CO2-eq/kg** for each recycling cycle (Using **Fimaq3D** production line), different than of a virgin filament (**1,95-1,84 kg CO2-eq/kg**, cradle-to-gate). [11][12]

Regarding performance, experimental evidence shows that **FFF** parts printed from **rPP** maintain mechanical behaviour comparable to virgin **PP** when process parameters are properly controlled. For an instance, from the **1st** recycling cycle to the **5th**, the polypropylene shows the following properties changes:

Tensile strength: **-37,94%** (31.1 → 19.3 MPa)
Elasticity Modulus: **-34,04%** (0.47 → 0.31 GPa)
Impact strength: **13,19%** (4.70 → 5.32 kJ/m²)
Flexural strength: **35,03%** (29.4 → 39.7 MPa)
Flexural Modulus: **51,02%** (0.49 → 0.74 GPa)

All properties still within application-viable ranges reported for additive manufacturing of **PP** [5].

Altogether, these results support the adoption of **rPP** in **FFF** to deliver functional, mass-customized components with a demonstrably lower carbon footprint and without material compromises that would preclude use in typical engineering applications [1][3][5].

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