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Research article

Variability of the declared recycled content by changing allocation methods: A case study on plastic waste recycling

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ABSTRACT

The Chain of Custody (CoC) standard tracks the recycled content (RC) of products, in most cases using the Mass Balance model. This model freely allows the selection of allocation methods and timeframes for the RC evaluation. Our work opens a discussion on the potential effects of this freedom in the RC evaluation. Firstly, we defined the general model representing the viable allocation methods and timeframe, and secondly, we applied the model to a case study. The mass balance model simplifies the monitoring of RC and encourages companies to use recycled materials. However, we outline the need for actions on stricter RC calculation and reporting, for instance, by reducing the timeframe of mass balance calculation or promoting the controlled blending model, which guarantees the physical presence of RC in the product. The results provide a basis for policymakers to set requirements for RC evaluation.

1. Introduction

The presence of Recycled Contents (RCs) in products has been increasingly tracked and disclosed by companies due to consumer demand and the European initiatives to promote recycling and the use of recycled materials (Stahel, 2016; Janik and Ryszko, 2017; European Commission, 2020; Abad-Segura et al., 2021; Rocchi et al., 2021; Chairat and Gheewala, 2023). This disclosure is usually done via third-party verified certifications or self-declarations regulated by ISO14021 (Howett, 1992; Kangun and Polonsky, 1995; Zuin, 2016; Kaur et al., 2018; Lahti et al., 2018; Romero-Hernández and Romero, 2018; Rhein and Schmid, 2020; European Commission, 2023b). However, there has been a lack of proper tracking of the RC along the product life cycle, resulting in potential greenwashing (de Freitas Netto et al., 2020; McGuinn et al., 2020). In particular, the European Commission has tackled the greenwashing problem with the recent European Directive proposal on the substantiation and communication of explicit environmental claims (European Commission, 2023a). The proposal also mentions the need for requirements regarding claims on RC, suggesting potential further provisions.

Currently, those requirements could be derived from the existing ISO22095 on the Chain of Custody (CoC) (REDcert2, 2018; ISO, 2020). The CoC standard, with its five models, aims to ensure the traceability of a material with *specific characteristics* (e.g. biological, recycled or from controlled sources) (Vidal et al., 2005; Thakur and Hurburgh, 2009; Storoy et al., 2013; Paluš et al., 2018; Beers et al., 2022) in a product along its entire life cycle (REDcert2, 2018; ISO, 2020) despite the fact no explicit requirements and guidance have been set at the European level. To date, several certification bodies have translated the five models into a specific set of requirements and approaches to implement each model, freely set by the certification bodies themselves (Zero Waste Europe, 2021; Braun et al., 2023).

However, not all the models provide the same level of traceability, and more importantly, the physical presence of the material with *specific characteristics* is assured only from the Identity Preserved to the Controlled Blending models, as shown in Fig. 1. When this cannot be guaranteed, the Mass Balance model might be selected to simplify the calculation with assumptions and drawbacks. The Mass Balance model uses a black-box approach where materials with and without *specific characteristics* are mixed, resulting in a product made of these mixed materials. However, several calculation aspects are not univocally set among certification bodies or established by the ISO or European Commission. These aspects are, for instance, the system boundaries, the scale of the mass balance, the physical mixing between the certified and non-certified materials, the allocation method, time periods used

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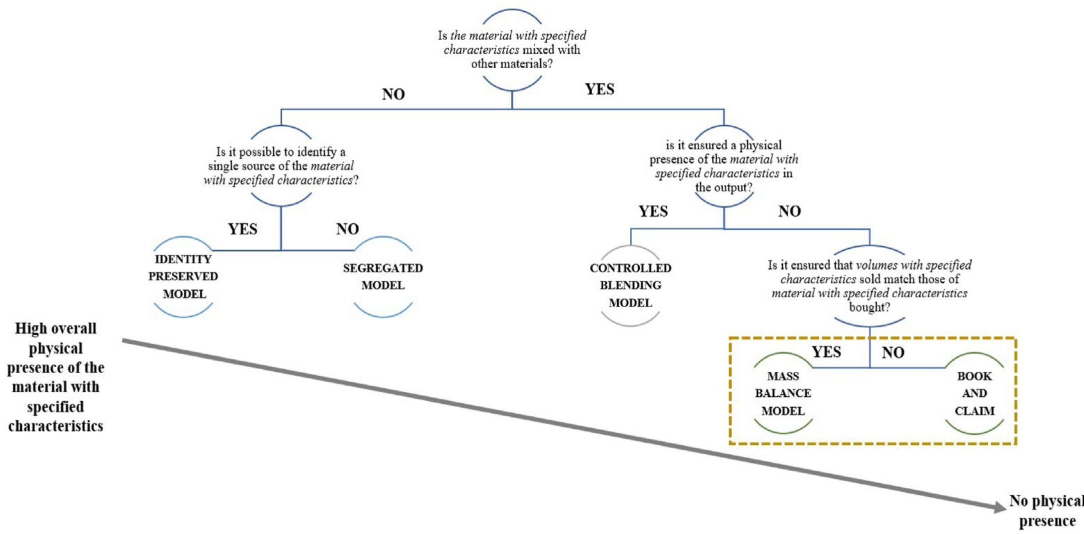

Fig. 1. Simplified logic scheme of the CoC's models tied to the physical presence of material with specific characteristics [8].

for the accounting, balancing and reconciliation process (Beers et al., 2022). Although the aspects and assumptions regarding the physical presence should be clearly stated in the claim, this lack of uniformity among certification bodies might hamper transparency and traceability to consumers (REDcert2, 2018; ISO, 2020; Zero Waste Europe, 2021; Braun et al., 2023).

The plastic industry is on the front line in adopting the CoC concept to estimate the RC of plastic in products. The European Commission is pushing the plastic industry to increase the recycling plastic content. However, although the EC sets minimum thresholds for plastic RC in products (Ragonnaud, 2023; European Commission, 2023c), best practices to calculate it are not yet provided, and the lack of appropriate RC assessment procedures may lead to several issues. First of all, there is not always the possibility (or the willingness) to monitor the mixing between virgin (i.e. derived from a source extracted directly from nature) and recycled plastic entering the manufacturing process, especially where there are no strict regulations regarding contamination or quality requirements. Secondly, the RC can be calculated with the Book and Claim model (also called "plastic credit" (Lee, 2021; Liu et al., 2021)), whose applicability and credibility have been widely discussed (Khadke et al., 2021; Sandhiya and Ramakrishna, 2021; WWF, 2021).

In this context, there is, thus, an urgent need to put the basis of a common approach for the evaluation of the RC to be accompanied by the minimum requirements that will be set by a regulatory body. The main challenge is tracking the RC along the product value chain, especially when the virgin and recycled materials are mixed. To the best of our knowledge, only a few authors have recently discussed RC claims from different perspectives. Iyer et al. (2023) opened the discussion on the variability of the declared RC claims based on the availability of recycled materials. Iyer et al. (2023) analysed the relationship between claims on the RC and the profit based on the availability and cost of sources. Conversely, position papers (ChemSec, 2021; United Nations Environment Programme, 2023) argued different views and opinions on using the Mass Balance model to assess the RC. On the one hand, the authors discussed the priority need of enhancing recycling and the use of recycled materials by simplifying evaluation methods. On the other hand, they also raised concerns about the reliability of these methods for companies manufacturing goods reliant on the quantity of recycled material incorporated into their products.

Following up on these existing studies, it is crucial to provide further scientific evidence on the effects of various methods on the RC calculation, which can be used to create a set of requirements in the context of European Regulations and initiatives. More specifically, this work narrows the discussion on the applicability of the different approaches of the Mass Balance model by analysing the variability of this model according to the approaches available for the plastic industry. Initially, a general model was developed for a product manufacturing process involving mixing virgin and recycled materials. Subsequently, various allocation methodologies and time frames for the Mass Balance model were identified. Then, an approach to conduct a comparative analysis of the RC of a product was outlined. Finally, this model was applied to a case study. The method introduced and adopted in this article can be reflected in any other sectors involving the uncontrolled mixing of virgin and recycled materials in products.

2. Methods

2.1. Theoretical approach

Our initial approach involved exploring a theoretical value chain composed of various process units and variables to answer our research question, as depicted in Fig. 2.

In order to decrease the number of variables to consider, the analysis was confined from a multi-stage to a single-stage process. This led to a reduction in the number of inputs (I) and outputs (Q) and focusing only on a single processing stage (OP).

The following Eqs. (1)–(4) were used as the base to compose the system, simulating the operations under investigation.

$$\overline{X}_j = \frac{\sum_i^n X_{j,i} * Q_{j,i}}{\sum_i^n Q_{j,i}} \tag{1}$$

$$Ri = \sum_j^m X_{j,i} * Q_{j,i} \tag{2}$$

$$\overline{\mathrm{x}_s} = \frac{\sum_i^n \mathrm{x}_{s,i} * Q_{j,i}}{\sum_i^n Q_{j,i}} \tag{3}$$

$$Ri = \sum_j^m x_{j,i} * Q_{j,i} \tag{4}$$

Where:

R_i is the mass of recycled material used as input in the system at time i.

$Q_{j,i,}$ is the output of one of the m products at the time i;

$\overline{\mathrm{X}}_{j,i}$ is the average RC in one of the m products in a time period from i to n;

$X_{j,}$ is the RC in one of the m products at the time i;

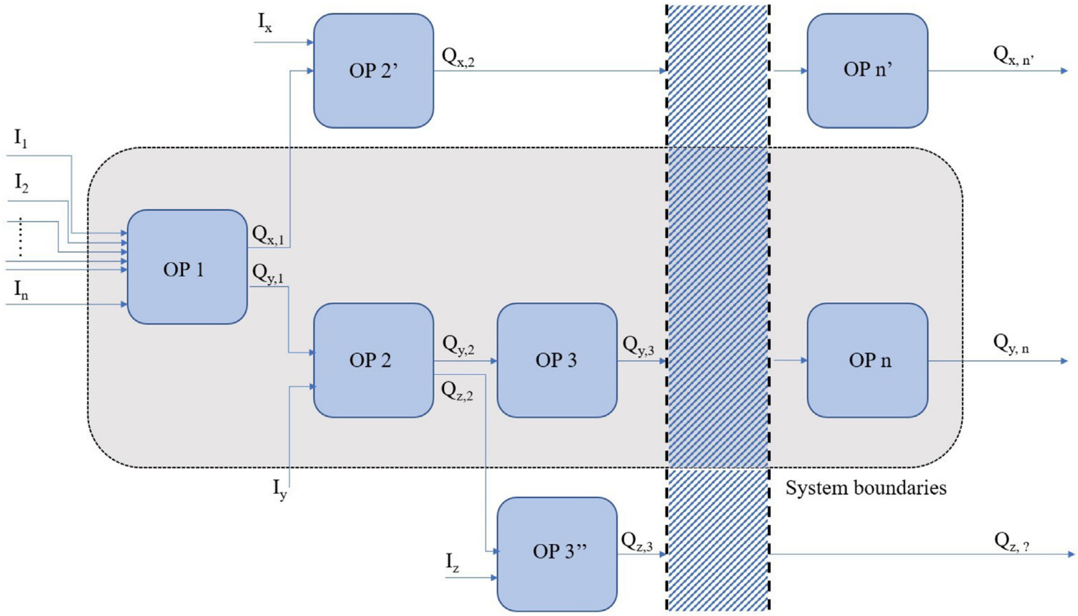

Fig. 2. Theoretical scheme of a multi-stage operation system with multiple inputs and outputs and an indeterminate number of unitary processes ($OP_{1,n}$), both inside and outside the boundaries of the process itself. $I_{1,2,n,x,y,z}$ represents the possible material inputs in the process, $Q_{x,y,z,i}$ represents the general output of specific units of the process. Material input can be virgin, secondary or mixed materials.

x_s is the declared RC in one of the m products in the specific scenario taken into account.

Further details on the equations and the methodology can be found in the supplementary materials.

2.2. Case study selection and description

After defining the theoretical scheme, the second step was to select a case study to test our research question. The case study and the theoretical approach were used to elaborate the scenarios for the simulation of a production process involving recycled and virgin materials. In particular, the case study has to fulfil the following criteria:

- A transformation process characterised by multiple material inputs and outputs;
- Inputs composed of both virgin and secondary materials;
- Variable compositions in the input and output streams.

A case study was identified within the LIFE project RESKIBOOT-LIFE19 ENV/BG/000059. LIFE projects are financed by the EU community to improve the environment and climate sustainability of products and processes. The chosen project focused on reusing plastic from end-of-life ski boots with the aim to prevent the disposal of 61 500 kg of waste thanks to the sorting and mechanical recycling of the ski-boot plastic components.

Ski-boots, mainly made of thermoplastic polyurethane (TPU) (Nanni et al., 2023), can re-enter the production chain by grinding the cuff and shell, obtaining a high-purity material used to produce new ski-boots by injection moulding (Colonna et al., 2013; Nanni et al., 2023). The project focused on mechanical recycling of TPU, even if a chemical recycling process, specifically depolymerisation, can also be applicable to cross-linked polyurethane (Kemona and Piotrowska, 2020; Wölfel et al., 2020).

The data on the TPU were gathered by the companies involved in the project. Then, the entering materials were classified according to their elastic module (E), which is representative of the TPU quality. This classification is essential as higher stiffness corresponds to increased costs and superior performance. According to the literature (Vidal et al., 2005) and the information obtained from ski-boot producers that participate in the LIFE project, TPU can be divided into the following three material classes (based on the Elastic module): (A) High-quality material, $E > 350$ MPa; (B) Medium quality material, $200 \text{ MPa} < E < 350$ MPa; (C) Low-quality material, $E < 200$ MPa. High-quality recycled TPU is reused for high-end ski-boots while softer materials for lower-end applications (e.g. junior boots).

In order to produce commercial materials with mechanical properties comparable to the original ones, the three material classes have to be extruded separately, adding some virgin polyurethane. Based on the project results, the amount of virgin materials strongly affects the properties of the output material.

In particular, a larger amount of virgin material allows to obtain a higher quality material than the input recycled TPU and, thus, to tailor the elastic modulus of the finished product. Using the LIFE project data, a simulated environment was developed to mimic the extrusion process, with twenty equations for ten variables (available as supplementary materials) aimed at predicting the process output.

In order to reduce the complexity of the system, efficiency-related losses were assumed to be equal to zero, considering their negligible effect on the RC reduction of all products.

2.3. Definition of the scenarios

As described in the introduction, two of the variables characterising the mass balance model are: (1) the allocation methods used for the RC and (2) the timeframe used to calculate the mass balance. Those two variables were tested by using the theoretical system in the selected case study.

Regarding the variability in the allocation methods for the RC, evaluation commenced by assessing the RC according to the data provided by the case study. Initially, the RC of ski-boots was computed using the controlled blending model of the CoC depicted in Fig. 1. The controlled blending model is a mass balance with all the inputs and outputs controlled. This was possible since all the flows were controlled and monitored throughout the mixing process between the recycled and virgin materials to ensure the desired quality of the final product (i.e. A, B or C).

Subsequently, a transition from a controlled system to an uncontrolled system was implemented by removing the quality requirements guiding the proportion between virgin and recycled materials in the final products. This step assumed three batches of products (A, B and C) produced with the same quality by mixing recycled and virgin materials differently according to the availability of both materials instead of the desired quality of products. Finally, three scenarios were defined for the uncontrolled system, representing different allocation methodologies for the mass balance model. The four chosen scenarios refer to possible methodology certification bodies adopt to certify the RC of companies' products as follows.

- **Controlled blending**: The declared RC equals the calculated value per the controlled blending CoC (the reference scenario).
- **Max economic value**: The most profitable characterisation that tries to maximise economic value, that firstly allocates declared RC to the most valuable product (A), then to the second one (B), and lastly to the less valuable one (C).
- **Proportional**: A proportional to the properties characterisation, with the declared RC that is allocated respecting the elastic module values, giving priority to class (A) material, then (B) and (C) class. This is a more conservative hypothesis than the previous one.
- **Conservative**: The conservative approach, in which the declared RC is allocated first to the less valuable product (C), then to the intermediate one (B), and lastly to the most valuable one (A). This conservative hypothesis was defined to better pinpoint the difference with his opposite, the Max economic value scenario.

Regarding the variability in the timeframe used to calculate the mass balance, the temporal variability of the process was simulated by randomly generating the stated variables. This approach resulted in the creation of 52 sets of data, which were then utilised to define a hypothetical year of production, enabling the aggregation of data in three-month periods.

The total production period represented by the data was divided into four smaller time intervals for mass balance, representing the four quarters of a production year. This division enabled observation of how different time reconciliations affect both the actual and declared RC. The time intervals have been chosen to represent better the ones generally used by companies that certify the RC in products (THE CIRCULATE INITIATIVE, 2021).

3. Results

The variability of the RC according to the selected allocation method for the mass balance model is shown in Fig. 3. The figure shows how adopting the allocation approaches *Max economic value, Proportional*, and *Conservative* affects the RC of the three classes of products for the first batch compared to the reference (i.e. *Controlled Blending*). If each product class is individually examined, the variability of the RC ranges from 20% (class B) to 100% (class C). The results obtained show how, ultimately, claims on RC can be "allocated" differently among products, not representing the physical presence of the RC in the claimed product.

Fig. 4 shows the variability in RC values grouped by product classes for each scenario and consequent allocation decision, referring to time-related batches in the case of batch reconciliation. Possible inconsistencies in the reporting can be inferred from Fig. 4 by observing the variability of RC values of different time-related batches. These inconsistencies can constitute an issue in the recycling industry, as making a verified claim containing precise RC for each batch would be complex and costly since it should require both proper sensorisation and a capillary tracking system for each process unit. To ease their labelling problem, the mass balance and its ability to reconcile multiple batch production have been analysed in this study, formulating several scenarios the industry may adopt for their claim.

The more significant range of variation can be found between the *max economic value* scenario and the *conservative* scenario. This relevant difference is tied to the opposite allocation logic on which the two scenarios are based. A critical point of this case study is that one of

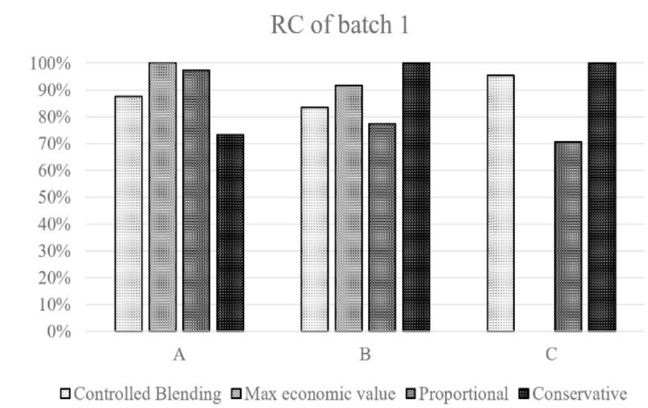

Fig. 3. Comparison of the RC for one batch calculated with different allocation methods.

the products, class A, has a higher output than the other two classes in most production batches. This has a significant impact on the RC attribution process; for instance, in batches t 17, 18, and 32, under the *max economic value* scenario where, the total RC is allocated to class A without maximising it, resulting in the content of both class B and C becoming null.

Besides these three outlier points, extreme variations in declared RC of class C TPU are observed in the *max economic value* scenario, plummeting to 0% on multiple occasions. It is worth noticing that this kind of phenomenon is not present in the conservative case, where the allocation is used to max both class C and B TPU, and this has to be tied to the difference in the output of the different batches, with A TPU being the most produced class. The *conservative* and *proportional* scenarios do not have any outliers, with all of them falling near their trend line. The RC of class C and B products fall into a trend line in multiple scenarios (*conservative* and *controlled blending*), which is tied to the equations' system used to transform the three products based on maintaining or increasing the product classes. Such equations, simulating the output of an extrusion process, are built in order that a C class product can only be produced from C class secondary material mixed with virgin TPU, making its RC for the *controlled blending* scenario constant. It can be noticed that the average RC for each scenario is not constant, as the constant value is tied to the total recycled mass while the RC represents the fraction of RC for each product. This can be easily seen in comparing the *conservative* scenario, where both class B and C products have a 100% RC while the RC of class A stays above 50%, with the *max economic value* scenario, where the RC of class C and for some batch of class B, is 0%.

With the average declared RC varying by more than 75% and punctual values approaching 100%, a substantial difference in the industry's claim can be asserted. This indicates the potential for generating products with the same physical and chemical properties but with different declared RCs or vice versa.

The complete data set for each batch of the four scenarios is reported in the supplementary materials.

4. Discussion

The Mass Balance model can be easily implemented by industries because it simplifies the calculation needed for environmental claims, as described in this study (Thompson, 2022). This methodology increases the willingness of industries to work with recycled materials, as it provides a more straightforward solution to calculate the RC, which should accelerate the transition to a more circular economy. However, this study raises concerns regarding the implementation of the Mass Balance by quantifying the variability of the potential claimed

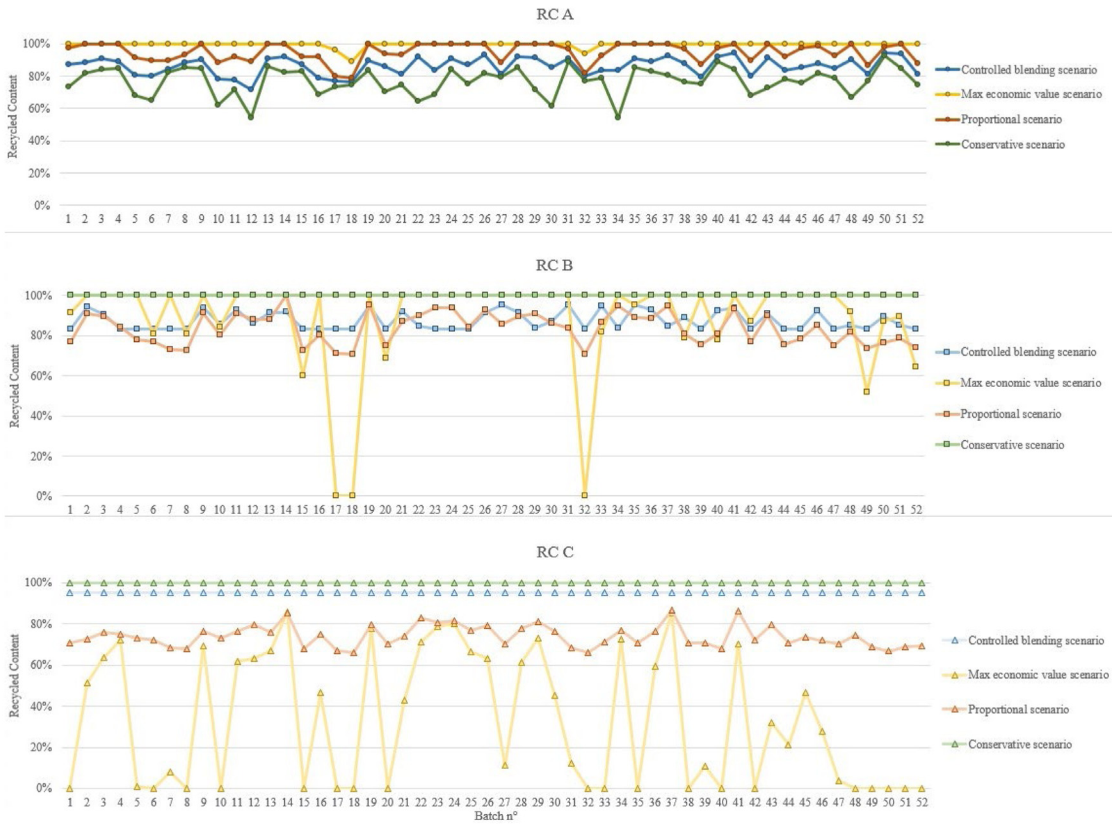

Fig. 4. RC variation from 0% to 100% for 52 batches of production. Furthermore for each product class RC is calculated according to four scenarios referring to possible methodology certification bodies adopt to certify the RC of companies' products as described in Section 2.3.

RC in products when adopting different approaches in the Mass Balance calculation.

The obtained results suggest a massive variability of the RC declarations according to the choices taken regarding several variables (e.g. allocation method or time frame). These findings mean that the "actual" RC in a product does not correspond to the "claimed" RC because of the freedom of choosing the boundaries of the Mass Balance model. The current lack of guidance for the calculation of RC in products could result in greenwashing issues. Whether the variability between the actual and the claimed RC might cause further implications needs to be investigated in the future with additional case studies, also among different sectors. Regardless, disclosing the methodology assumptions employed in the calculation is crucial.

The set of requirements for environmental claims regarding the RC should focus on the identification of the permissible options for the Mass Balance definition. The authors recommend adopting the Control Blending instead of the Mass Balance model for the RC calculation, as it monitors the physical presence of the RC in the product. If not applicable, a stricter range of possibilities for the definition of the variables should be considered when applying the Mass Balance model.

This study suggests some of these options that can be further considered by policymakers and regulators in setting those requirements, specifically for the allocation methods and time frame variables. Regarding the former, there is a need to investigate further the consequences of different allocation methods, especially downstream of the supply chain. For instance, if intermediate recycled materials (e.g. polyester) are used to produce a final product (e.g. T-shirt), there might be further variability regarding the overall RC in the T-shirt based on the declared RC of the material used. In the absence of foreground data on one of these processes, perspective analysis, including the process stage up to the consumer gate, could emphasise effective variance in RC. The latter could be addressed by considering a reduced time frame (e.g., one month or less) for the mass balance calculation to increase the RC claims' reliability.

5. Conclusions

The only current reference to track and calculate the RC in a product is the ISO22095 on the Chain of Custody (CoC). However, several certification bodies have freely translated the CoC standard into sets of requirements, which are not uniquely set or defined. This is particularly crucial when the recycled material is mixed with the virgin material; hence, the overall RC in the final product is difficult to track. Simultaneously, the absence of a defined set of requirements for the RC calculation could lead to several issues, such as potential greenwashing of environmental claims, challenges in product comparison, and unharmonised approaches to tracking the RC along the life cycle of a product.

The need to establish rules regarding RC declaration has also been recognised by the European Commission, which is oriented to provide a common framework for quantitative assessment of environmental claims (European Commission, 2023a). For instance, the Mass Balance model of the CoC standard considers different allocation methods or timeframes for calculation, which can be freely chosen by certification bodies. Therefore, this paper aims to provide insights that could assist the European Commission in establishing minimum requirements by analysing the variability of the RC in a product through the adoption of different allocation methods and timeframes for the Mass Balance. The primary outcome of such work regards the following points:

- Setting targets for RC without specifying the chosen Mass Balance method shall result in a discrepancy in the levels of RC in products. This is necessary when comparing different performances among players in the supply chain or even within the same organisation.

- The differences between the average and the actual declared RC can be remarkably evident if different assumptions are adopted. This variability could eventually generate problems tied to inconsistency in the material's property, even when the allocation is fixed at the batch level.
- The RC used as a circularity indicator can vary significantly depending on the tracking approach used. This variability can affect the value of such information, as the different methodologies provide different claiming strategies.
- Effect of the tracking approach in a circular economy context could introduce a further magnitude of uncertainty once a further combination of recovering processes is present in the recycling chain (e.g. thermo-decomposition treatment plus mechanical recycling). This lack of information could propagate through the entire value chain and impact the final users.

This study suggests the use of the Control Blending model, which currently can guarantee the highest physical presence of the RC in a product when possible. The authors recognise the benefits of the Mass Balance model; however, they caution against its excessive use in the plastic recycling industry and underline the necessity of providing standards for the application of the Mass Balance. Proper use of this methodology should be paired with quantitative methods to assure consistency of declarations among actual and claimed contents. One option to tend towards the controlled blending model is to reduce the timeframe for the calculation, for instance, by reducing it to one month while introducing progressive improvements in information reliability and constant independent verification. This study provides first insights into the variability in results by changing some variables in the mass balance. Future analyses should investigate whether this variability of the RC between the actual and the claimed RC might cause further implications, especially downstream in the product value chain (e.g. for an intermediate product containing a recycled material).

CRediT authorship contribution statement

Francesco Caraceni: Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Elisabetta Abbate:** Conceptualization, Writing – original draft, Writing – review & editing. **Carlo Brondi:** Conceptualization, Methodology, Project administration, Writing – review & editing. **Martino Colonna:** Investigation, Resources. **Giovanni Dotelli:** Project administration, Supervision. **Andrea Ballarino:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resenv.2024.100154.

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