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Research Paper

Quality degradation in glass recycling: substitutability model proposal

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ABSTRACT

The sustainability assessment of waste management systems requires tools capable of evaluating material quality degradation during recycling. Existing research has predominantly focused on the development of substitutability models for plastics, leaving a gap in addressing other materials like glass. Glass is commonly regarded as endlessly recyclable, even though its actual recyclability depends on several crucial factors, such as colour and pollutant contamination. Many Life Cycle Assessment (LCA) studies in this field assume a one-to-one substitution coefficient, neglecting material deterioration and inaccurately representing real-world scenarios. This study proposes and assesses a substitutability model for glass, aiming to measure the replacement extent between virgin materials and recycled crushed glass (cullet). The methodology is based on two key factors: technical quality substitutability, considering impurities and colour contaminations in cullet, and market applicability, accounting for market demand. Once formulated, the model was applied to a European case study on glass waste treatment. Two scenarios were considered: one assuming complete substitution between cullet and raw materials, the other incorporating quality degradation. Findings indicate that, accounting for quality degradation, only 83% of cullet effectively replaces raw materials, resulting in a decrease of the benefit associated with recycling of 13–23% for the different examined impact categories, compared to complete replacement assumption. This underscores the importance of considering quality deterioration in glass recycling impact assessments.

1. Introduction

1.1. Aim of the paper

Over the past century, the world has witnessed a remarkable surge in both population and economic development, giving rise to a dual challenge: environmental degradation and economic issues. The main cause lies in the way goods are produced, consumed and, once they have become waste, disposed (European Commission, 2019). Addressing these challenges requires a shift from a linear to a circular economic model, focusing on improved consumption habits and more sustainable production processes. In 2015, the European Union (EU) introduced its first circular economy action plan (European Commission, 2015), which encompasses a comprehensive array of measures involving the entire life cycle of a product: from production and consumption to waste management and the secondary raw materials market. The ultimate goal is to extend the life cycle of products, preserving their value for as long as possible while minimizing waste generation (European Commission, 2014). This can be achieved through various actions feasible at different stages of a product's life (*i.e.* during its design, production or end of life phases): one such measure is recycling. Recycling plays a crucial role in reintroducing materials into the market and reducing reliance on virgin materials. However, it can lead to quality degradation due to alterations in mechanical properties or contamination with other materials during collection and sorting phases (Rigamonti et al., 2018). It is then necessary to define the extent to which raw materials can be replaced with secondary materials, but the lack of consistent and universally standardized regulations within the EU makes this task challenging (European Commission, 2015). Achieving high-quality recycling is of significant importance within the EU, as highlighted by the Waste Framework Directive (European Commission, 2008). Nevertheless, the lack of consistent guidelines concerning recycling quality hinders the achievement of optimal efficiency.

Life Cycle Assessment (LCA) methodology can be employed to evaluate recycling benefits and drawbacks. However, most of LCA studies on waste management often assume a one-to-one (1:1)

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substitution ratio, implying that secondary materials fully replace the virgin ones (Rigamonti et al., 2020). This assumption does not accurately reflect reality and can lead to incorrect evaluations of the environmental benefits associated with recycling.

This article aims to establish a methodology for assessing the quality degradation of glass during recycling and quantifying the substitutability of virgin materials with resulting secondary materials. The proposed framework is built upon existing studies and specifically targets glass, given the lack of investigations in the current literature. The novelty of this manuscript lies in the application of the developed model in a case study that incorporates data provided by stakeholders of the sector. Assessing quality deterioration provides more realistic evaluations, offering a better understanding of the advantages and drawbacks associated with glass recycling.

1.2. *Glass sector*

In 2022, the EU produced 38.5 million metric tons of glass, with 64 % attributed to container glass, 28 % to flat glass, 3 % to domestic glassware, 2 % to continuous reinforcement fibers, 2 % to special glass and 1 % to others (Statista, 2023).

Glass is commonly regarded as an endlessly recyclable material, although the extent of its recyclability is influenced by several crucial factors and varies across countries. Indeed, once glass becomes a waste, it undergoes a recycling process involving several consecutive steps, each characterized by a specific efficiency that collectively determines overall effectiveness. This recyclability is significantly impacted by losses occurring at three key stages of the waste treatment: during collection, sorting, and distribution of crushed glass (known as cullet) to various end markets (Grant et al., 2022). The most substantial losses, primarily attributed to issues like colour and pollutant contamination, take place during the initial collection stage. The method chosen for glass collection plays a crucial role in determining its potential circularity. For instance, using a separate collection system reduces the presence of impurities, making a larger portion of cullet suitable for glass manufacturing. This leads to higher recycling rates compared to mixed systems that collect glass with other materials. Furthermore, separate glass collection can be executed in two ways: by mixing various glass colours or maintaining them separated (Grant et al., 2020). The former approach leads to greater losses compared to the latter, as additional sorting is required if one wants to segregate cullet by colour, ultimately reducing recycling efficiency.

The economic value and potential applications of cullet are influenced by various factors, encompassing its physicochemical composition, colour, presence of impurities and homogeneity within its specifications (Grant et al., 2020). These characteristics can hinder the glass manufacturing process for different reasons, limiting the functionality and the applicability of recycled glass. For example, contaminants, both metallic and non-metallic inorganic materials (ceramics, stones, and porcelain, often referred to as CSP), can interfere with the remelting process due to issues like incorrect colouring, furnace damage or defects in the final glass product. Additionally, colour is a crucial attribute and once compromised its recovery becomes unattainable (Grant et al., 2020). There are four primary glass colours in production: clear (flint), green, amber, and mixed (Joint Research Centre, 2011). Clear glass production necessitates the presence of minimal coloured cullet, followed by amber glass, which comparatively tolerates more colour contamination. Consequently, clear and amber cullet hold higher value compared to green, as green glass permits higher levels of colour impurities. In conclusion, the overall efficiency, the decreased reliance on raw materials and the market acceptance of secondary materials all contribute in determining the advantages of recycling (van der Harst et al., 2016).

When evaluating the environmental impacts of glass recycling, an LCA study can be conducted following the ISO 14040 and ISO 14044 standards, and challenges related to multifunctionality need to be addressed. Multifunctionality occurs when a process serves multiple functions, such as recycling, which combines waste management and material production. Dealing with multifunctionality can be achieved through different approaches, one of these being system expansion with substitution. This approach implies the identification of external monofunctional processes that provide products or functions equivalent to those of the co-products of the considered multifunctional process. These monofunctional processes are commonly subtracted from the multifunctional one in order to estimate the impacts of the co-function of interest based on which the functional unit is defined (Rigamonti et al., 2020). However, substitution introduces significant challenges, especially when quantifying the extent of functional equivalence and substitutability between products (Rigamonti et al., 2020). Considering potential quality degradation during waste treatment, often referred to as downcycling (Rigamonti et al., 2018), is essential for assessing properly the environmental impacts of glass recycling. Furthermore, developing a methodology capable of determining the substitutability of virgin materials with cullet is imperative. The following sections present the considerations that led to the development of the proposed methodology.

1.3. *Brief overview on quality degradation models in literature*

An initial bibliographic research conducted in the Scopus database using the keywords "*glass, recycling and quality degradation*" guided the selection of the articles listed in Table 1. These papers served as primary references for developing the substitutability model proposed in this study. As one can see, many of the findings align with the concepts introduced by Vadenbo et al. (2017), are predominantly focused on plastic waste and are anchored in either market dynamics or technical functionality. Within LCA studies, approaches grounded in technical functionality have found more extensive due to the inherent volatility of market prices and the challenges associated with sourcing comprehensive data, both of which can lead to inconsistent results (Huysveld et al., 2022). However, it is important to acknowledge that determining physical parameters proves complex as well (Rigamonti et al., 2020). Among the references provided in Table 1, Roosen et al. (2023) is the only one applying the proposed framework to a case study focused on glass recycling. However, it is worth noting that the evaluation of technical substitutability in their manuscript primarily relies on literature data. The authors themselves acknowledge this approach as a limitation, highlighting the importance of incorporating industry experience for a more comprehensive assessment.

2. Material and methods

2.1. *Setting up the substitutability model*

Among the references listed in Table 1, the study by Golkaram et al. (2022) plays a key role in the development of the substitutability model proposed in this paper. In their research, they presented a methodology for assessing the technical quality substitutability of recycled plastics by defining a dimensionless parameter derived from multiple properties (*e.g.* mechanical properties, impurities content, odour). For each analysed property (*i*), the parameter (X_i) quantifies the ratio between the difference in value between the property's ideal scenario (I_{ideal}) and the actual sample (I_{sample}) and the accepted range across all secondary applications of that property ($I_{min} - I_{max}$) (Eq. (1)) (Golkaram et al., 2022). Therefore, X_i represents the normalized deviations of I_{sample} from I_{ideal} and whenever the sample value falls outside the acceptable range, the parameter is set to 0.

$$X_i = \frac{(I_{ideal} - I_{sample})_i}{(I_{min} - I_{max})_i} \quad (1)$$

The model incorporates the importance of the various criteria through

Table 1
Articles found during literature review where substitutability models are proposed.

Reference	Case study application field	Peculiarity of method
Vadenbo et al. (2017)	Organic waste	Substitution potential is determined as a function of the: physical resource potential, resource recovery efficiency, market response and substitutability. Substitutability is calculated as the degree of functional equivalence between recovered material and displaced material.
Kampmann Eriksen et al. (2019)	Plastic waste	Substitutability, like in Vadenbo et al. (2017), depends on the functionality of the recovered material and the virgin material. Functionality is itself a function of market shares and applicability, which is defined by the quality of secondary material.
Rigamonti et al. (2020)	Bottom ashes from incineration and plastic waste	Based on Vadenbo et al. (2017) model. Here the substitutability coefficient is determined identifying the main technical property needed for the key functionality of the considered material.
Demets et al. (2021)	Plastic waste	The technical substitutability is calculated based on two factors. The first one concerns the mechanical requirements for a specific application and represents different mechanical properties needed. The latter reflects the processability of plastic and is determined through a function based on relevant flow properties.
Golkaram et al. (2022)	Plastic waste	The model considers various properties (*i.e.* mechanical, processability, odour and colour) and accounts for the importance of the different characteristics through weighting factors.
Huysveld et al. (2022)	Plastic waste	Substitutability is determined as a function of both market and technical substitutability. The first factor accounts for the difference in the market caused by legislative restrictions and is calculated based on the model of Kampmann Eriksen et al. (2019). The latter accounts for quality degradation, determined using a simplified version of the method proposed by Demets et al. (2021).
Roosen et al. (2023)	Plastic waste and glass waste	The quality assessment of recycling is based on three dimensions: the substitutability and functionality of the resulting secondary material, along with the environmental impact of the recycling process. Moreover, the evaluation of substitutability follows the methodology proposed by Vadenbo et al. (2017) and is based on literature data mainly provided by the Joint Research Centre (2011).

weighting factors (j_i), enabling the calculation of quality reduction for each property according to Eq. (2). Overall quality substitutability (ξ) is determined through Eq. (3). Further details on the methodology parameters and applicability can be found in the work by Golkaram et al. (2022).

$$\xi_i = \frac{1}{(1 + |X_i|)^{j_i}} \tag{2}$$

$$\xi = \prod \xi_i \tag{3}$$

To apply the model by Golkaram et al. (2022) to glass, the properties to be used in the model itself should be defined. The framework proposed by Grant et al. (2020) has been considered to this aim. Indeed, Grant et al. (2020) proposed a comprehensive framework for assessing cullet quality through the establishment of categories based on physico-chemical type, colour, and presence of contaminants. These categories, ranging from A to E, determine potential secondary applications of cullet. In particular, category A is suitable for specific colour container glass production, whereas category B for abrasive applications, darker colour container glass manufacturing, and other remelting applications (glass wool). Categories C through E, with varying contaminant restrictions, correspond to non-remelt uses and aggregate purposes.

Due to the great difficulties encountered in finding data relating to all the properties proposed by Grant et al. (2020) in their theoretical framework, the model developed in this paper solely considers as key quality attributes colour contamination and impurities. Table 2 shows the data regarding acceptable pollutants concentrations and colour contamination requirements for different cullet applications collected by analysing the related literature and contacting various Italian companies affiliated with the glass industry and recycling sector.

2.2. *The proposed substitutability model*

The substitutability model proposed in this paper is based on the classification of cullet by quality. Two elements were identified as central in the characterization of each quality category: technical quality substitutability and market applicability.

First, the framework proposed by Grant et al. (2020) and explained in Section 2.1 has been considered for the definition of the quality categories. However, the proposed approach focuses solely on categories A and B for two main reasons. Firstly, these categories meet the more stringent criteria for secondary materials applications. Secondly, external cullet, primarily originated by post-consumer glass (Beerkens et al., 2011), finds extensive use in container glass and glass wool production (Schmitz et al., 2011). A further departure from Grant et al. (2020) is the distinction based on the number of recycling loops for specific applications. Within the realm of container glass, categories A and B present ample opportunities for recycling loops. In contrast, glass wool materials exhibit limited recyclability due to inherent constraints, while abrasive applications preclude further recycling. Consequently, abrasive applications were omitted and category B was subdivided into two distinct subcategories: B1 and B2. B1 corresponds to dark-coloured glass containers (amber and green containers), while B2 pertains to glass wool materials. As category B1 already encompasses dark-coloured glass container, category A's secondary application was limited to the exclusive production of flint glass container. Additionally, colour constraints were included within category B1, while they were omitted for B2 due to their lower importance in determining its application.

Then, to assess technical quality substitutability, the model developed by Golkaram et al. (2022) for plastic was adopted, as anticipated in Section 2.1. Impurities content and colour contamination have been identified as key quality aspects for cullet. Acceptable intervals for impurity requirements were primarily dictated by the end-of-waste criteria (Joint Research Centre, 2011), with the ideal value for pollutant content set at 0. Colour requirements were defined based on the least conservative limits among those listed in Table 2. Impurity content and colour contamination were treated as equally important since there was no available information regarding their relative significance. The pollutants category was further divided into five quality factors for categories A and B1 and four for B2, accounting for the most relevant pollutants. In

Table 2
Limits on impurities and colour contamination according to different organisations/ standards.

Organisation/ Standard	Fe metals (ppm)	Non-Fe metals (ppm)	Inorganics (ppm)	Organic (ppm)	Heavy metals (ppm)	Flint (%)	Amber (%)	Green (%)
BSI/WRAP PAS 101 [(a)]	–	–	–	–	–	$>$ 94 % flint	$>$ 85 % amber	$>$ 70 % green
BV Glass Standard sheet T 120 [(b)]	5	5	50	500	200	$<$ 0.3 % amber $<$ 0.2 % green $<$ 0.2 % coloured	$\geq$ 80 % amber $<$ 10 % green	$\geq$ 75 % green $<$ 10 % amber
Company in the container glass sector	2	3	20	300	–	$>$ 99 % flint	$>$ 80 % amber	$>$ 75 % amber
Company in the insulation sector	5	5	20	500	–	–	–	–
End of waste criteria for glass cullet [(a)]	50	60	100	2000	–	–	–	–
Eurima [(a)]	10	20	25	3000	–	–	–	–
FERVER [(a)]	10	60	100	2000	–	$>$ 98 % flint	–	–
Packaging directive [(c)]	–	–	–	–	200	–	–	–

(a) Joint Research Centre (2011).
(b) Bundesverband Glasindustrie e.V. (BV Glas), Bundesverband der Deutschen Entsorgungs-, Wasser- und Rohstoffwirtschaft e.V. (BDE), Bundesverband Sekundärrohstoffe und Entsorgung e.V. (BVSE) (2014).
(c) European Commission (2001).

category B2, a more tolerant range was considered concerning organics, while heavy metals were excluded as its application is not related to food sector. Given the limited information, equal weighting coefficients were assigned also to each identified subcategory. These assumptions guided the definition of the information required to determine technical quality substitutability coefficients for each category, following the methodology proposed by Golkaram et al. (2022). It is important to note that Golkaram et al's index pertains to plastics, whereas the current study focuses on glass. In order to distinguish the two different application fields, a decision was made to label the technical quality substitutability coefficient (ξ) as quality coefficient (Q) in the proposed model. For reference, Tables 3 and 4 summarize data for categories A, B1 and B2.

The substitutability of virgin materials is also influenced by both the intended market for secondary materials and their demand levels. Considering potential market shares that cullet can achieve is crucial. Market shares (*MS*) for each quality category were calculated based on the data collected for the two examined applications glass container and glass wool, as described in Eq. (4) and Eq. (5). According to Statista (2023), Europe produced 23,700,000 t of glass container in 2020 ($P_{container}$). In the same year, the European thermal insulation market reached 265,800,000 m^3, with 33.3 % corresponding to glass wool (IAL Consultants, 2022). Assuming an average density value of 48.8 kg/m^3, the 2020 production of insulation glass wool amounted to 4,322,307 t ($P_{glasswool}$). The resulting *MS* for glass container and glass wool are shown in Eq. (4) and Eq. (5), respectively.

$$MS_{container} = \frac{P_{container}}{P_{container} + P_{glass\ wool}} = 84.6\% \tag{4}$$

Table 3
Parameters related to impurities content used in the calculation of quality coefficients pertaining to categories A, B1 and B2. The intervals ($I_{min} - I_{max}$) allow the assessment of whether cullet belongs to a given category based on its characterization.

Category	Impurities	$I_{min} - I_{max}$ (ppm)	I_{ideal} (ppm)	j_i
A (Flint glass container)	Fe metals	0–50	0	0.1
	Non-Fe metals	0–60	0	0.1
	Inorganics	0–100	0	0.1
	Organics	0–2000	0	0.1
	Heavy metals	0–200	0	0.1
B1 (Dark-coloured glass container)	Fe metals	0–50	0	0.1
	Non-Fe metals	0–60	0	0.1
	Inorganics	0–100	0	0.1
	Organics	0–2000	0	0.1
	Heavy metals	0–200	0	0.1
B2 (Insulation glass wool)	Fe metals	0–50	0	0.25
	Non-Fe metals	0–60	0	0.25
	Inorganics	0–100	0	0.25
	Organics	0–3000	0	0.25

Table 4
Parameters related to colour contamination considered in the calculation of quality coefficients pertaining to categories A, B1 and B2. The intervals ($I_{min} - I_{max}$) allow the assessment of whether cullet belongs to a given category based on its characterization.

Category	Other accepted colours	$I_{min} - I_{max}$ (%)	I_{ideal} (%)	j_i
A (Flint glass container)	Than flint	0–6	0	0.5
B1 (Dark-coloured glass container [(a)])	Than amber	0–20	0	0.5
	Than green	0–30	0	0.5

(a) The secondary application of cullet within this quality category can involve the production of either amber or green glass containers, depending on colour requirements.

$$MS_{glass\ wool} = \frac{P_{glass\ wool}}{P_{container} + P_{glass\ wool}} = 15.4\% \tag{5}$$

To distinguish between colourless and coloured glass container, the production shares for the year 2020 were determined using Prodcom data, providing statistical information on the production of manufactured goods across enterprises in EU countries. Specifically, two product codes were considered: 23131140 and 23131150. The former represents colourless glass bottles with a nominal capacity $<$ 2.5 L for beverages and foodstuffs (excluding bottles covered with leather or composition leather, infant's feeding bottles), while the latter is associated with coloured bottles having the same characteristics. Production shares related to the production of coloured or colourless containers were assumed to be the same as that of bottles, as no specific information were found for all the containers. According to Eurostat (2023), European production in 2020 for 23131140 and 23131150 amounted to 16,650,073,646 pieces ($P_{colourless}$) and 28,815,372,304 pieces ($P_{coloured}$), respectively. From the available data, the production shares of colourless ($MS_{colourless,container}$) and coloured glass container($MS_{coloured,container}$) for the year 2020 were determined according to Eq. (6) and Eq. (7).

$$MS_{colourless,container} = \frac{P_{colourless}}{P_{colourless} + P_{coloured}} = 36.6\% \tag{6}$$

$$MS_{coloured,container} = \frac{P_{coloured}}{P_{colourless} + P_{coloured}} = 63.4\% \tag{7}$$

The market share for each analysed quality category (A, B1 and B2) for the year 2020 was then calculated as follows:

$$MS_A = MS_{container} \cdot MS_{colorless,\ container} = 31.0\% \tag{8}$$

$$MS_{B1} = MS_{container} \cdot MS_{colored,\ container} = 53.6\% \tag{9}$$

$$MS_{B2} = MS_{insulation} = 15.4\% \tag{10}$$

In conclusion, the formulated methodology entails the following steps: 1) identifying potential secondary applications for cullet by comparing its characterization with the requirements listed in Tables 3 and 4 for each quality category; 2) calculating the actual quantity of cullet in each category based on their respective market shares; 3) calculating the quality coefficients (Q), representing the overall quality reduction resulting from recycling, for each quality category; 4) calculating cullet that can effectively replace raw materials in glass production by multiplying the calculated amount by the quality coefficients.

This critical analysis provides insights into the potential impact of quality degradation on the substitutability of cullet for traditional raw materials in glass manufacturing.

2.3. *Case study*

2.3.1. *Description of the system*

The proposed model is applied to a case study involving the treatment of glass waste within the European context. The main goals are to test the applicability of the developed approach, assess the substitutability coefficient and evaluate the environmental impacts associated with the system. This assessment combines data provided by an Italian sorting plant, the ecoinvent database (Database ecoinvent 3.8, 2021) and information found in related literature.

The sorting plant manages an annual volume of 300,000 t (m_{in}) of waste packaging glass (assumed as functional unit in the LCA study) and operates at an 85 % efficiency rate, meaning that only 255,000 t is actually recyclable ($m_{recyclable}$). The system boundary, as illustrated in Fig. 1, includes the transportation of collected glass waste to the sorting plant and its subsequent treatment. During the sorting process, extraneous fractions like metals, plastics, and infusible materials (CSP) are removed. Additionally, due to European food industry regulations regarding heavy metals, lead glass is also separated. Cullet is sorted based on its dimension and coloration. The fine fraction ($<$3 mm) undergoes sieving since optical sensors cannot accurately differentiate it from CSP. As there are no end-of-waste criteria for this fraction, it is treated as waste and is not included in the recycling process. Another screening process targets cullet with a size between 3–10 mm, as optical sensors are unable to sort them by colour, resulting in the creation of a mixed coloured stream. The only fraction categorized according to the cullet's colour by the optical sensors is the one with dimension $>$ 10 mm. Overall, the sorting process classifies three distinct streams, each characterized by the following shares: 16 % for flint ($m_f = 40{,}800$ t), and 42 % for both darker-coloured ($m_d = 107{,}100$ t) and mixed-coloured ($m_m = 107{,}100$ t).

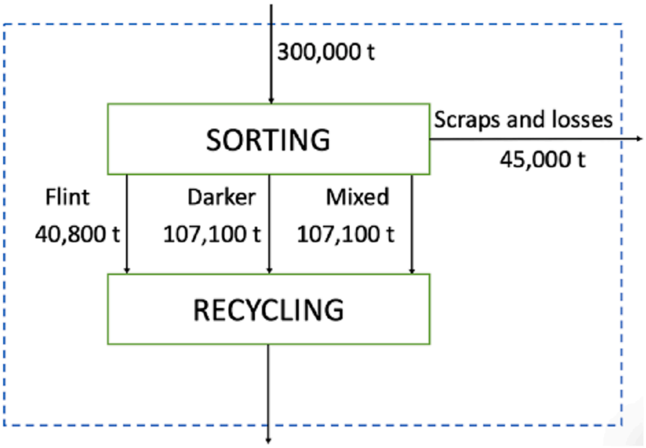

Fig. 1. Analysed system.

2.3.2. *Calculation of the model parameters*

The impurities content and colour composition of the three output streams (Table 5) were derived from data provided by two Italian companies involved in glass recycling. However, colour composition of the mixed stream was assumed to replicate the hypothetical combination of the flint and darker-coloured streams, as no information were given.

Based on the ecoinvent database (Database ecoinvent 3.8, 2021), the end-of-waste criteria (Joint Research Centre, 2011) and the data provided by CoReVe (CoReVe, 2021), the virgin glass was assumed to comprise 61.0 % silica sand, 18.5 % soda-ash, 12.5 % limestone, 6.0 % dolomite and 2.0 % feldspar. To manufacture 1 kg of glass, 1.20 kg of raw materials are required. Alternatively, the production of 1 kg of glass necessitates 1 kg of cullet (Rigamonti and Grosso, 2009). The relationship between substitutable raw materials (m_{rm}) and available cullet (m_c) is thus established as:

$$m_{rm} = 1.20 \bullet m_c \tag{11}$$

To assess the impact of quality deterioration on substitution, two scenarios are considered. In the baseline scenario (Scenario 1:1), material degradation is disregarded and a 1:1 substitution ratio is assumed. In this scenario, cullet suitable ($m_{c,1:1}$) for raw materials replacement is simply equivalent to $m_{recyclable}$:

$$m_{c,1:1} = m_{recyclable} \tag{12}$$

In the alternative scenario (Scenario QD), downcycling is taken into account and the quality coefficient (Q) has to be considered. Cullet suitable ($m_{c,QD}$) for raw materials replacement is determined as:

$$m_{c,QD} = Q \bullet m_{recyclable} \tag{13}$$

To evaluate cullet's potential secondary applications, a comparison between the characterization of the three outputs (Table 5) and the corresponding constraints (Tables 3 and 4) is necessary. The distribution among suitable quality categories depends on their respective market shares and demand. If the secondary material fails to fulfil quality standards for a particular category, its use as a replacement within that category becomes unfeasible. However, if demand in the other categories is high and the secondary material adheres to their quality requirements, it can serve as substitute. Conversely, if the quality is low for a specific category and demand in other quality categories is saturated, substitution becomes unfeasible even if it meets the limitations. In this study, it is assumed that the demand for cullet within each quality category is consistent. This implies that if quality requirements for a specific category are not met, but cullet complies with the criteria of the remaining two categories, reallocation occurs in the higher-quality category among the two. This reallocation is determined based on the market share initially intended for the original category. Under these assumptions, the allocation of cullet from the three identified streams is distributed among the three quality categories as follows.

Table 5

Impurities content and colour contamination characterizing the three streams obtained from the sorting process.

	Flint stream	Darker stream	Mixed stream
Impurities (ppm)			
Fe metals	5	5	5
Non-Fe metals	5	5	5
Inorganics	25	25	25
Organics	300	300	300
Heavy metals	10	10	10
Colour (%)			
Flint	99.5	15	38
Amber	0.5[a]	5	62[a]
Green		80	

[a] This value refers to amber + green.

The flint stream satisfies quality requirements for categories A and B2. Consequently, no cullet from this stream is allocated in category B1 ($m_{f,B1} = 0$ t). The amounts of cullet allocated to categories A ($m_{f,A}$) and B2 ($m_{f,B2}$) are determined by applying market shares to flint stream's mass (Eq. (14) and (15)). Material originally intended for B1 is reallocated to category A instead of B2, as a preference exists for allocating material to the higher-quality category when requirements are met.

$$m_{f,A} = (MS_A + MS_{B1}) \bullet m_f \tag{14}$$

$$m_{f,B2} = MS_{B2} \bullet m_f \tag{15}$$

The darker-coloured stream meets the requirements for categories B1 and B2 ($m_{d,A} = 0\ t$), while the material originally intended for category A is reallocated to category B1. However, the content of amber cullet in this stream (5 %) is too low to allow the production of amber containers, as it is required to be > 80 %. Therefore, cullet belonging to category B1 will only contribute to the production of green containers. The amounts of cullet allocated to categories B1 ($m_{d,B1}$) and B2 ($m_{d,B2}$) are determined by applying market shares to the mass of the darker-colour stream, as outlined in Eq. (16) and Eq. (17).

$$m_{d,B1} = (MS_A + MS_{B1}) \bullet m_d \tag{16}$$

$$m_{d,B2} = MS_{B2} \bullet m_d \tag{17}$$

The mixed-coloured stream only meets the requirements for category B2 ($m_{m,A} = m_{m,B1} = 0\ t$). The amount of cullet allocated to category B2 ($m_{m,B2}$) is determined as follows:

$$m_{m,B2} = (MS_A + MS_{B1} + MS_{B2}) \bullet m_m \tag{18}$$

In this way the total cullet assigned to each category can be calculated for both scenarios.

Then, for Scenario QD, the quality coefficients Q can be calculated for each quality category following the methodology described in Sections 2.1 and 2.2 and considering data of Tables 3, 4 and 5. The next step involves assessing for both scenarios the respective replaceable raw materials by applying the defined relationship in Eq. (11).

With the degree of substitution examined for both scenarios in each quality category, the following step involves a comprehensive exploration of the environmental impacts associated with each one. This examination will enable a detailed comparison, contributing to determine the influence on the results derived from LCA analysis.

The reduction in impacts related to the use of cullet in glass production depends on various factors. Firstly, it prevents the sourcing and production of raw materials, including their transportation to the glass manufacturing plant. Secondly, there are energy savings at the furnace of about 2.0–3.0 % with every 10 % of cullet in the melting mass (Joint Research Centre, 2013). Thirdly, replacing carbonate raw materials with cullet, which has already undergone thermal decomposition, significantly reduce process CO_2 emissions. Notably, using 90 % of cullet in the melting mass results in an 89.2 % reduction in process CO_2 (Rigamonti and Grosso, 2009).

The avoided impacts ($I_{avoided}$) related to the use of cullet in glass manufacturing are determined as the difference between impacts generated from production without cullet ($I_{without\ cullet}$) and those with a certain amount of cullet (I_{cullet}). Considering the three cullet destinations, *i.e.* flint glass container (category A), green glass container (category B1) and glass wool (category B2), impacts are evaluated accordingly (Eq. (19)):

$$I_{avoided} = \sum \frac{(I_{without\ cullet} - I_{cullet})_i \bullet m_{c,i}}{p_i} \tag{19}$$

Where $m_{c,i}$ represents the mass of cullet suitable for raw materials replacement for each quality category in the two scenarios, calculated accordingly Eq. (12) and Eq. (13), and p_i corresponds to the cullet content for the three production processes (0.605 $kg_{cullet}/kg_{product}$ for flint container production, 0.835 $kg_{cullet}/kg_{product}$ for green container production, and 0.797 $kg_{cullet}/kg_{product}$ for glass wool production (database ecoinvent 3.8, 2021)).

The overall impacts (I_{tot}) of the examined systems are due to the transportation of glass waste to the sorting plant ($I_{t,sorting}$), the sorting process itself ($I_{sorting}$), the transportation of the sorted cullet to the manufacturing facility ($I_{t,recycling}$) and the avoided impacts related to the use of cullet (Eq. (20)):

$$I_{tot} = I_{t,sorting} \bullet m_{in} \bullet d + I_{sorting} \bullet m_{recyclable} + I_{t,recycling} \bullet m_{recyclable} \bullet d - I_{avoided} \tag{20}$$

The already existing datasets[1] within the ecoinvent database 3.8, and the characterization model "*EF 3.0 Method (adapted) V1.02 / EF 3.0 normalization and weighting set*" are used for the assessment.

3. Results

The methodology described in the previous sections enabled the assessment of cullet's potential to replace raw materials amid quality degradation during recycling. In the absence of downcycling (Scenario 1:1), 255,000 t of cullet holds the potential to replace 306,000 t of raw materials, assuming complete substitution. However, accounting for quality degradation (Scenario QD) reveals varying impacts across examined categories, as detailed in Table 6. Overall, only 83 % of cullet proves effective in replacing virgin materials, representing a decrease of approximately 17 % compared to the complete substitution assumption of Scenario 1:1. This implies that 1 kg of cullet can qualitatively replace approximately 1 kg of primary materials, contrasting the 1.20 kg of Scenario 1:1. Table 6 also illustrates that the calculated quality coefficients remain consistent for the three streams within each category. This is due to both the assumed characterisation of the samples (Table 5) and the considered limitations (Tables 3 and 4). However, it is important to specify that these coefficients may vary among categories and individual streams.

Table 7 summarizes variations in each examined impact category compared to the complete replacement assumption. Notably, quality deterioration from recycling results in a 13–23 % increase in all 16 impact categories, consequently diminishing the benefits associated with recycling. Among the categories, ozone depletion is the most significantly affected, showing a 23.4 % increase compared to the assumption of complete replacement. These findings underscore the importance of considering the actual replacement ratio between raw materials and cullet in LCA analysis, as environmental impacts are strongly influenced by these considerations.

4. Discussion

The developed approach relies on a series of assumptions and simplifications that have facilitated its implementation, but have also distanced it from real-world situations. Two elements contribute primarily to its generalizations. The first factor is the scarcity, if not

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[1] Packaging glass, white {GLO}| packaging glass production, white, without cullet | Cut-off, U; Packaging glass, white {RER w/o CH+DE}| production | Cut-off, U; Packaging glass, green {GLO}| packaging glass production, green, without cullet | Cut-off, U; Packaging glass, green {RER w/o CH+DE}| production | Cut-off, U; Glass wool mat {GLO}| production, without cullet | Cut-off, U; Glass wool mat {CH}| production | Cut-off, U; Transport, freight, lorry 16–32 metric ton, EURO5 RER| transport, freight, lorry 16–32 metric ton, EURO5 | Cut-off, U; Glass cullet, sorted {RER}| treatment of waste glass from unsorted public collection, sorting | Cut-off, U. All the considered datasets of production were modified to consider the European electricity mix. In the datasets of glass production with cullet, impacts associated with cullet processing were excluded since they are already accounted for in Eq. (20).

Table 6
Cullet available for substitution and resulting replaceable raw materials determined for each category in both considered scenarios. Presented quality coefficients are related only to Scenario QD.

			Quality coefficient		Replaceable raw materials (10^3t)	
Category	**Stream**	**Cullet (10^3t)**	**Scenario 1:1**	**Scenario QD**	**Scenario 1:1**	**Scenario QD**
A	Flint	34.5	1.0	0.91	41.5	37.5
	Darker-coloured	0	1.0	0.91	0	0
	Mixed-coloured	0	1.0	0.91	0	0
B1	Flint	0	1.0	0.73	0	0
	Darker-coloured	90.6	1.0	0.73	108.7	79.4
	Mixed-coloured	0	1.0	0.73	0	0
B2	Flint	6.3	1.0	0.88	7.5	6.7
	Darker-coloured	16.5	1.0	0.88	19.8	17.5
	Mixed-coloured	107.1	1.0	0.88	128.5	113.6
	Total	**255.0**	**1.0**	**0.83**[a]	**306.0**	**254.7**

[a] The overall quality coefficient is the weighted mean of the quality coefficients determined for the three quality categories.

Table 7
Total impacts assessed for each impact category in both scenarios, with the corresponding percentage increase from Scenario 1:1 to Scenario QD.

		Total impact		Variation
Impact category	**Unit**	**Scenario 1:1**	**Scenario QD**	
Climate change	kg CO_2 eq	−1.51E+08	−1.27E+08	+16.1 %
Ozone depletion	kg CFC11 eq	−2.61	−2.00	+23.4 %
Ionising radiation	kBq U-235 eq	−1.69E+07	−1.47E+07	+13.0 %
Photochemical ozone formation	kg NMVOC eq	−2.92E+05	−2.42E+05	+17.0 %
Particulate matter	disease incidence	−8.27	−6.88	+16.8%
Human toxicity, non-cancer	CTUh	−1.64	−1.37	+16.5%
Human toxicity, cancer	CTUh	−1.09E-01	−9.17E-02	+16.0%
Acidification	mol H^+ eq	−7.40E+05	−6.23E+05	+15.8%
Eutrophication, freshwater	kg P eq	−5.11E+04	−4.40E+04	+13.9%
Eutrophication, marine	kg N eq	−9.81E+04	−8.16E+04	+16.9%
Eutrophication, terrestrial	mol N eq	−1.56E+06	−1.30E+06	+16.7%
Ecotoxicity, freshwater	CTUe	−5.74E+09	−4.69E+09	+18.2%
Land use	Pt	−1.01E+09	−8.22E+08	+18.7%
Water use	m^3 deprived	−8.39E+07	−7.17E+07	+14.5%
Resource use, fossils	MJ	−1.48E+09	−1.26E+09	+14.9%
Resource use, minerals and metals	kg Sb eq	−1.51E+03	−1.27E+03	+16.3%

complete absence, of existing literature in this domain. Secondly, companies within this sector have shown limited willingness to share their data, representing a significant obstacle during the data collection phase.

One key constraint of the model is the exclusive focus on quality categories pertaining to remelt applications, neglecting numerous other potential applications. Moreover, to accurately compute the quality coefficient, a broader spectrum of quality attributes beyond those currently under analysis should be considered. These may include chemical composition, grain size and moisture content. Furthermore, the present model assigns them equal weight due to data limitations, whereas accounting for varying degrees of importance among the criteria should be achieved. The value of the quality coefficient is also strongly influenced by the tolerance intervals assumed for the three quality categories. However, defining these ranges is challenging, primarily due to the variability in quality requirements. In this study, a decision was made to consider the more conservative requirements from those listed in Table 2, while disregarding less stringent ones obtained from contacted companies. Standardized methods considering international variations in quality constraints need to be developed in order to homogenize tolerance intervals and strengthen the foundation of the model. Moreover, validation across different case studies and regions is needed to ensure the methodology's versatility and reliability.

Despite its limitations, the proposed model represents a valuable initial step towards assessing the environmental impacts associated with systems considering glass downcycling. Its implementation would enable stakeholders in the glass industry to more accurately assess raw material substitutions and savings, thereby facilitating a more realistic evaluation of the industry's environmental footprint. Furthermore, by providing a more truthful assessment of impacts, policymakers could develop or update regulations and policies based on more reliable information, thus contributing to more sustainable practices in the industry.

In conclusion, accounting for material downcycling would enable decisions to be informed by more accurate and realistic data. Future research should prioritize addressing the limitations highlighted in this study. Simultaneously, greater data sharing and collaboration between industry stakeholders should be encouraged. These combined efforts have the potential to increase both the accuracy and applicability of the proposed model.

5. Conclusions

Glass is often perceived as an endlessly recyclable material, even if recycling process can lead to quality degradation. However, the existing literature is rather lacking and the majority of LCA studies on waste management neglect this deterioration, resulting in assessments that inaccurately represent real-world scenarios. This article aims to bridge this gap by introducing a substitutability model for glass, considering both technical quality substitutability and market applicability. It is important to acknowledge that the proposed methodology relies on assumptions and simplifications, aimed at facilitating its implementation, that potentially distance it from reality. However, it serves as a valuable starting point, emphasizing the need for future research to overcome its limitations. Additionally, increased transparency and collaboration within the industry organizations are crucial, as the response rate during this study proved to be quite low.

The model was applied to a European glass waste treatment case study, exploring two different scenarios. The baseline scenario assumes a 1:1 substitution, while the alternative considers quality degradation of cullet. According to the model, only 83 % of cullet effectively replaces virgin materials in the alternative scenario, indicating a 17 % decrease compared to the complete substitution assumption. Consequently, LCA analysis showed a 13–23 % decrease of the benefits of the recycling activity compared to the baseline scenario.

This study underscores the complexity of glass recycling, stressing the significance of including quality deterioration in environmental assessments. Recognizing the unrealistic nature of assuming a complete substitution, an alternative proposal is to consider an 83 % actual replacement between raw materials and recycled glass. It is important to note that this percentage was derived from the most tolerant limitations gathered, not accounting for the more stringent requirements provided by the sector's companies. Despite relying on case-specific assumptions, this approach offers a more realistic perspective than assuming complete replacement. The accurate assessment of substitutability between virgin and recycled materials is crucial for evaluating raw materials savings and environmental impacts, contributing to the selection of more sustainable waste management practices. Moreover, it enables a more truthful assessment of glass products' life cycle impacts, as waste management should be included in every product LCA.

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CRediT authorship contribution statement

Paula Martina Barbato: Writing – original draft, Software, Methodology, Data curation. **Emma Olsson:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Lucia Rigamonti:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization.

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.

Data availability

Data will be made available on request.

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