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Quality of recycling: Urgent and undefined

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ABSTRACT

Quality of recycling is a concept used by many authors in the scientific literature and the EU legislator. However, a clear definition of what is intended for quality of recycling and a framework for operationalising it is lacking. Most studies, while proposing indicators reflecting quality, leave the concept of quality largely undefined. Such lack of clarity is an obstacle to the conception of robust policies addressing recycling and circular economy. In this article, we review the available studies investigating on recycling quality, synthetize the approaches available and conclude suggesting a way forward for research to operationalise the definition to support circular economy policy measures and monitoring.

Essentially, quality is not an on/off criterion. The definition of quality of recycling should consider that quality depends on technical characteristics of the recyclate, which determine if it is adequate (thus functional) for a certain end application or not. Furthermore, it should consider that the recyclate can be used in different end applications over different markets and that can be adequate for substitution of primary resources in certain applications, but less or not in others. At system-wide level, this results in a certain degree of virgin resource substitution. To this end, preserving functionality, i.e. minimising the recyclate loss of functions via functional recycling, is key. Drawing upon studies on waste management, life cycle assessment and resource dissipation, we link the concept of functionality to substitutability of virgin resources and broader suitability in the circular economy, striving to show the linkages between different perspectives.

1. Introduction

Quality of recycling is a rather fuzzy concept, at the same time acknowledged as very important and left undefined in EU *acquis* and scientific literature. The EU Waste Framework Directive (European Commission, 2018) repeatedly mentions that recycling should be steered towards high-quality without providing a rigorous definition. Most of the scientific studies, while proposing indicators reflecting quality, leave the concept of "quality" undefined (e.g. see Eriksen and Astrup, 2019; Haupt et al., 2017; Roithner & Rechberger, 2020 where indicators are proposed but rigorous quality definitons are essentially missing). While acknowledging the extensive discussion and research in the field of Life Cycle Assessment (LCA) concerning substitutability (i.e. the degree to which a secondary material can replace a primary one; notably Vadenbo et al., 2017), this is nevertheless only one aspect of the broader concept of recycling quality. In particular, we found a few studies that explicitly attempt to define quality while operationalising the definition (Demets et al., 2021; Eriksen, Damgaard, et al., 2018; Grant et al., 2020). A lack of clarity on what quality means is a crucial obstacle to the conception of robust policy measures addressing recycling in a broader context of circular economy and as a tool to achieve the highest possible resource efficiency. This article aims to review the available studies tackling recycling quality, synthetize the approaches available and suggest a possible way forward for research with the aim to operationalise the definition to support circular economy policy measures and monitoring.

Abbreviations: CE, Circular Economy; DKR, Deutsche Kunststoff Recycling; EoL, End-of-Life; EU, European Union; HDPE, High Density Polyethylene; LCA, Life Cycle Assessment; LCIA, Life Cycle Impact Assessment; PE, Polyethylene; PEF, Product Environmental Footprint (as recommended by EU Commission); PET, Polyethylene Terephthalate; PP, Polypropylene; PRE, Plastic Recyclers Europe; UNEP, United Nations Environmental Programme.

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2. Literature review on quality of recycling

Since definitions and approaches are very diverse, we will: i) report keywords used in the literature to directly or indirectly refer to recycling quality (Section 2.1), ii) describe the main approaches available (Sections 2.2–2.4), and iii) drawing upon these, discuss and propose possible avenues for an operational framework applicable in EU policy (Sections 3–5). This paper has a main focus on materials related to solid waste management, such as plastics, metals, glass, and paper. Many examples that will be given throughout this paper are on these material types as the discussion on quality of recycling is very timely in these sectors. Yet, this paper is not explicitly including or excluding certain material groups or, in broader sense, resources. It highlights the need for a more overarching quality framework in the circular economy, which can be further tailored towards specific material or resource groups, but which is needed for circular economy policy-making.

2.1. Keywords and terms used to refer to quality

The literature uses different keywords (Table 1) when referring to quality recycling. “Technical quality” or “technical characteristics” of recyclates (i.e. secondary materials obtained as output of recycling) are intuitively key factors relevant to quality, but this would require testing standards and materials databases as discussed in Demets et al. (2021). The terms “function” or “functionality”, in turn synonymous with “utility”, are rather well-known and used in the field of functional recycling of metals (notably UNEP, 2011). Functional recycling has clear connections with high-quality recycling as opposed to low- or non-functional recycling, where the properties that made the material desirable in the first place are reduced or irreversibly lost (Table 1). In this context, the terms dissipative versus non-dissipative flows are also used to say something about the potential remaining/future functionality of materials in resource efficiency-related research (Table 1; notably Beylot et al., 2020). In LCA, the concept of quality is most often related to the effective “substitutability” of primary (virgin) material by the recyclate (Table 1; notably Rigamonti et al., 2020), which is clearly dependent on quality. Other terms include the circularity potential and recyclability potential or suitability in circular economy (CE), which reflects the ability of a recycling system to close material loops. Open/closed-loop recycling are expressions that have been used since long, sometimes with direct implications related to quality of recycling, however with controversial consequences. Closed-loop is in fact typically considered synonym of high-quality, whereas connections between open-loop and quality can be less straightforward (Huysman et al., 2017), especially when the terms downcycling and upcycling are used without properly defining what is ‘up’ and what is ‘down’.

Although there are sometimes no explicit ‘scientific’ references to quality, industry themselves set quality definitions and criteria specifically on the recycled material. In case of closed-loop recycling, the same type of companies (e.g. beverage-packaging manufacturers) are performing the recycling, setting rules they themselves follow (whether or not by standardised methods, e.g. DKR minimum requirements by the Deutsche Kunststoff Recycling or PRE specifications; PRE, 2018). For pre-consumer waste, this can even be within the company, which does not require an explicit definition of quality as the company knows the materials and end-product requirements. In case of post-consumer waste having explicit rules becomes more relevant, as in this case the quality language needs to be spoken over companies in a value chain (sorting/recycling/manufacturer/processor/brand owner). Finally, for open-loop recycling, this is even the case over the life cycles of different sectors, which call for explicit rules of quality as different sectors are involved. It derives that, in a growing circular economy where different sectors will be interconnected, a definition of quality becomes important.

The following explicit or implicit definitions of quality of recycling, or proxies for it, have been identified through a literature review. Existing interpretations are as disparate as relating to chemical purity,

Table 1
Keywords and terms used in the scientific literature with reference to quality of recycling. We distinguish between concepts that refer to the quality of the material itself and those that refer to the quality of the system.

Keywords and terms[1]	Definition (implicit/explicit)[2]	Used by[3]
Impurity content	Content of untargeted materials and/or substances in a targeted waste stream destined to recycling/reprocessing (material-specific concept).	Alassali et al. (2020); Eriksen, Pivnenko, et al. (2018); Faraca et al. (2019); Pivnenko et al. (2014, 2016); Muchova et al. (2011); Muchová & Eder (2010); Rodriguez Vietez et al. (2011).
Technical quality	Example for plastic: the technical quality of plastics is a result of mostly mechanical properties, typically complemented with a property that describes the flow behaviour of the melt phase (Demets et al., 2021; material-specific concept).	Demets et al. (2021).
Technical characteristics (properties)	The technical properties that give the material the ability to fulfil the required functions. For example, for plastics the properties are generally divided into mechanical and processability characteristics (Demets et al., 2021; material-specific concept).	Many authors; e.g.: Demets et al. (2021); Eriksen & Astrup (2019); Grant et al. (2020); Rigamonti et al. (2020).
Function/Functionality	A defined bunch of physical and chemical properties that made the material desirable in the first place (material-specific concept).	Many authors; e.g.: Eriksen, Damgaard, et al. (2018); Eriksen & Astrup (2019); Hahladakis & Iacovidou (2018); Peiró et al. (2018); UNEP (2011); Vadenbo et al. (2017); Stewart & Weidema, (2005).
Functional recycling[4]	Recycling in which the physical and chemical properties that made the material desirable in the first place are retained for subsequent use (system-wide concept).	Many authors; e.g.: Guinée et al. (1999);Diener & Tillman (2015); Eriksen, Damgaard, et al. (2018); Graedel et al. (2011); Hahladakis & Iacovidou (2018); Peiró et al. (2018); Reck & Graedel (2012); Stewart & Weidema (2005); UNEP (2011); Vadenbo et al. (2017);
Resource dissipation/Dissipative flows	Dissipative flows of abiotic resources are flows to sinks or stocks that are not accessible to future users due to different constraints. These constraints prevent humans to make use of the function(s) that the resources could have in the technosphere (system-wide concept; Beylot et al., 2020).	Berger et al. (2020); Beylot, et al. (2020, 2021); Ciacci et al. (2015, 2016); Matos et al. (2020); Passarini et al. (2018); Stewart & Weidema (2005).
Substitutability	The degree of functional equivalence between alternative resources/products for a specific end-use (Vadenbo et al., 2017).Also called substitution ratio or displacement/substitution factor (material-specific concept). For example for plastics: a measure of the functionality of the recycled plastic divided by the functionality of the substituted virgin plastic (Vadenbo et al., 2017).	Many authors; e.g.: Civancik-Uslu et al. (2021); Rigamonti et al. (2020); Rigamonti et al. (2009); Vadenbo et al. (2017)..

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Table 1 (*continued*)

Keywords and terms[1]	Definition (implicit/ explicit)[2]	Used by[3]
Circularity potential	The ability of individual recycled fractions to fulfil quality demands in a steady-state market representing a closed material loop situation (Eriksen, Damgaard, et al., 2018; system-wide concept).	Eriksen, Damgaard, et al. (2018)
Downcycling vs Upcycling	Recycling process whereby the recycled material is used for a lower-quality market application than that of the previous life cycle, normally defined by a lower market value, as opposite to upcycling (system-wide concept), defined for plastics as: 'the use of plastic waste, post-industrial or postconsumer, as a feedstock for the synthesis of value-added products, being polymers, molecules, or materials' (Jehanno et al., 2022)	Haupt et al. (2017); Koffler & Florin, (2013); Eriksen, Damgaard, et al. (2018); Rigamonti et al. (2020). Jehanno et al. (2022)
Closed-loop vs Open-Loop Recycling	Closed loop is a recycling process whereby the recycled material is reused for the same market application as that of its previous life cycle (system-wide concept). Open loop is a recycling process whereby the recycled material is used for a different market application than that of the previous life cycle (system-wide concept).	Many authors; e.g.: Andreasi Bassi et al. (2022); Geyer et al. (2019); Haupt et al. (2017); Graedel et al. (2011); UNEP (2011).

[1] Keywords were used to retrieve studies from Scopus, Sciencedirect and Google search. The studies were then further screened and only those studies containing a theoretical/operational approach to quality of recycling and/or a definition of quality of recycling were retained.

[2] Whenever the "Definition" is taken from a specific study, the associated reference is reported. Alternatively, a reasonable definition based on the literature is given.

[3] The list of sources is not exhaustive.

[4] Term coined by Guinée et al. (1999).

environmental benefits, or suitability in CE.

2.2. Approaches/definitions based on the impurity content

The content of impurities is sometimes used to reflect quality of recycling. Recently, Alassali et al. (2020) considered plastics derived from various types of waste from electrical and electronic equipment to evaluate their quality for recycling by measuring the concentration of potentially toxic elements, focusing on cadmium, lead, mercury, and chromium, in addition to flame retardant as bromine and antimony. A similar approach to quality was taken by Eriksen, Pivnenko, et al. (2018) for household plastic waste, by Faraca et al. (2019) for wood waste collected at recycling centres (centralised municipal collection points), and by Pivnenko et al. (2014, 2016) for paper waste. End-of-waste criteria for metals and the international standards also define quality grades of the collected and sorted scrap input-to-reprocessing based on impurities (Muchova et al., 2011; Muchová & Eder, 2010); likewise for glass (Rodriguez Vietez et al., 2011). It should be noticed that these studies focused on the impurities of the waste input-to-recycling or -reprocessing, except for Eriksen, Pivnenko, et al. (2018) that analysed both waste-sent-to-recycling and recycled material. There may be differences between the content of contaminants in the waste-to-recycling and in the final recycled material/product due to decontamination steps occurring in the recycling/reprocessing (exemplified for the case of paper in Pivnenko et al., 2016).

2.3. Approaches/definitions based on functionality and substitution

UNEP (2011) defines functional recycling for metals as the portion of the End-of-Life (EoL) recycling in which the metal in a discarded product is separated and sorted to obtain recyclates that are returned to raw material production processes that generate a metal or alloy. Based on this definition, BIO by Deloitte (2015) propose that functional recycling *refers to recycling in which the element in a discarded product is separated and sorted to obtain secondary material displacing same primary material.* Non-functional recycling *refers to recycling in which the element in a discarded product is collected and incorporated in an associated large magnitude material stream* (e.g. copper incorporated in a flow of stainless steel). *This represents the loss of its function as it is generally impossible to recover it from the large magnitude stream* (concept also used in Dewulf et al., 2021). The concept of functional/non-functional recycling has been applied to determine the recovered flows of raw materials in EU, including Critical Raw Materials (Matos et al., 2020; Passarini et al., 2018; Peiró et al., 2018). Furthermore, the EU End-of-Waste criteria for metal scraps include the concepts of functional recycling and quality of the materials that cease to be waste (e.g. content of foreign materials, absence of visible oil, oily emulsions, lubricants or grease, etc.; see Council of the European Union, 2011; European Commission, 2013; Muchova et al., 2011; Muchová & Eder, 2010; Rodriguez Vietez et al., 2011). However, the application to the case of other materials, e.g. plastic, is less straightforward because of the many applications and often low recyclability. A polymer such as polyethylene (PE)-bottle can be recycled at EoL into PE-piping and thus substitute virgin plastic (i.e. the same primary material according to the definition of functional) contributing to the overall supply of plastic to the market. However, this incurs a loss of the original functionality of the material, i.e. the technical characteristics that made it desirable for the original application are not necessarily preserved (see Demets et al., 2021). Specifically, the additives used as a barrier in PE-bottles would be recycled into PE-pipes with no use/function there. In this respect, the alternative definition of functional recycling provided in UNEP (2011) and aligned with Grant et al. (2020) seems more appropriate, i.e. *recycling in which the physical and chemical properties that made the material desirable in the first place are retained for subsequent use.*

Grant et al. (2020) explicitly define quality as *the extent to which, through the recycling chain, the distinct characteristics of the material (the polymer, or the glass, or the paper fibre) are preserved or recovered so as to maximise their potential to be re-used in the circular economy*. These characteristics vary by material but may include, for example, food-contact suitability, structural characteristics (i.e. uniformity and viscosity), clarity and colour, and odour. The same authors link their definition to the practical utility of the material in the circular economy, and on identifiable characteristics of materials within the (recycling) value chain. Such a definition starts from preserving functionality while at the same time moving away from open/closed-loop concepts. The authors also provide concrete examples of quality category for recycled packaging materials (plastics, glass, and paper/cardboard).

Eriksen, Damgaard, et al. (2018) propose a definition and an explicit classification of quality for recycled plastic based on the market application. Quality is defined after Vadenbo et al. (2017) as *the degree of functional equivalence between alternative resources/products for a specific end-use* and a classification in high-quality, medium-quality and low-quality is proposed. The classification is based on literature and legislation for the current applications of plastics in EU (Plastics Europe & EPRO, 2016).The authors assign high-quality to materials approved for food contact, representing the strictest legal material requirements; medium-quality to materials that can be used for toys, pharmaceuticals, and electrical and electronics, representing lower and varying legal material requirements; and low-quality to materials with minimal legal requirements like plastic for building/construction, automotive or the non-food packaging sector. The authors further propose to go beyond substitutability and mass-based recycling rates by looking at the potential of closing material loops in the long-term in a steady-state market ("circularity potential" of a recycling system). The circularity potential indicator (a number between 0 and 1, where 1 is the highest quality) is proposed, measuring the ability of the material to substitute high-quality virgin material, for which the circularity potential is set to 1. For recycled products, the circularity potential would equal the amount of functionally recycled material multiplied by the potential market share of the application group. For example, food-grade plastic is given a potential market share of 1 (i.e. maximum) because it can, according to the authors, in principle be used for all (high-, medium-, and low-quality) market applications.

As a follow up of their previous work, Eriksen et al. (2019) assessed the thermal degradation, processability and mechanical properties of a range of reprocessed polyethylene terephthalate, polyethylene, and polypropylene (PET, PE and PP, respectively) samples from source separated household plastic waste and evaluated the potential for closed-loop recycling by comparing such properties to those of the correspondent virgin materials. The authors assessed and compared melt flow index, tensile strength, tensile strain and impact strength for secondary and primary samples of PET, PE and PP.

Demets et al. (2021) propose a method to quantify the technical substitutability associated with a recycled plastic material based on the functionality, which depends on the intended application and is determined by a series of technical (mechanical and processing) characteristics. The authors thus define the mechanical and processability recycling quality. The mechanical quality refers to how well the mechanical requirements of the intended application of the recycled material (e.g. pipes, packaging film, bottles, etc.) are fulfilled, while the processability quality refers to the simplicity of processing (e.g. how suitable is the material for injection or blow moulding). Both parameters are calculated relative to the virgin counterpart used for that intended application, conforming to the formula suggested in Vadenbo et al. (2017). The overall technical substitutability is calculated as the minimum between the mechanical and processability recycling quality, and represents how good is the quality of the recycled material for the intended application relative to the virgin counterpart. The study applies the framework to three commercial plastic products.

A similar approach is taken with recycled aggregates in Blengini and Garbarino (2010) and Borghi et al. (2018) who classify aggregates according to different quality levels, based on technical characteristics and requirements specified in EN or national construction product standards for specific constructive uses. Rigamonti et al. (2020) look at quality from the perspective of the technical substitutability of secondary materials relative to primary ones for use in waste LCA studies, using a set of case studies. Sixteen technical substitutability coefficients are provided for individual waste fractions ranging from paper, high-density PE (HDPE), PP or mixed plastic waste, to recycled aggregates. The approach differs from that of Demets et al. (2021) in that only one main technical property is considered as representative of the functionality of the material for an intended final application of the recyclate. It derives that the calculation of the substitutability coefficient is simpler than in Demets et al. (2021)

Building on Vadenbo et al. (2017), Haupt et al. (2017) perform an in-depth analysis of the recycling of paper, cardboard, aluminium, tinplate, glass and PET from municipal solid waste in Switzerland by splitting the recycling rates into closed-loop and open-loop collection rates and recycling rates, also adapting the UNEP (2011) definitions. The authors conclude that open-loop recycling maximizes the amount of recyclate, but is irreversible as the secondary material is degraded in quality and cannot be further recycled. In turn, closed-loop recycling emphasizes quality aspects and allows the return of the recycled material to the application in the previous service life. They conclude that the recycling rates are insufficient to describe the performance of the circular economy, as they fail to describe the actual effect on circularity, i.e. the extent to which the recovered material can effectively provide the desired service or functions (displace virgin material). An explicit definition of quality is not provided, but implicitly the authors refer to closed-loop as to a scenario of higher quality.

Hahladakis and Iacovidou (2018) define quality as *the remaining functionality (*i.e. *described via the remaining properties and characteristics) of material, components, and products once they become secondary materials*. Quality measures to which extent the specifications of manufacturers (or recyclers, when dealing with sorted waste) are met. While such definitions are not operationalised to a case study, they are aligned with the approach of Demets et al. (2021), Eriksen, Damgaard, et al. (2018), Grant et al. (2020); Rigamonti et al. (2020).

2.4. Approaches/definitions based on functionality and resource dissipation

There is a consistent portion of the LCA literature focusing on resource indicators, which has connections with quality recycling through the concept of functionality. Stewart and Weidema (2005) start from the concept of functionality to quantify the impacts of resource dissipation in LCA, and consider high-quality those secondary resources in which the original functionalities of the resource under assessment are maintained or increased (vice versa they refer to low-quality output when functionalities are decreased or to resource made unavailable when dissipated/irreversibly lost). The authors propose the use of thermodynamics concepts such as entropy (e.g. concentration in the recovered flow) to define the quality of the secondary resource, e.g. metals, and propose the concept of ultimate quality limit as the lowest boundary of quality under which the resource is not anymore available due to technology/economic limitations. This is operationalised in the work of (Ciacci et al., 2015, 2016; Matos et al., 2020; Passarini et al., 2018) who quantify the global/EU dissipation of elemental metals via material flow analyses, considering non-functional metal recycling as a dissipative resource flow likewise emissions or non-recovery (disposal/incineration) and building upon previous work on functional recycling of metals (notably Graedel et al., 2011; Reck & Graedel, 2012). The work of UNEP/IRP (2020) on how to improve the quantification of impacts on natural resources also links to the concept of value/functionality. Berger et al. (2020) suggests that *within the area of protection "natural resources", the safeguard subject for "mineral resources" is the potential to make use of the value that mineral resources can hold for humans in the technosphere. The damage is then quantified as the reduction or loss of this potential caused by human activity*. While the study again emphasises the centrality of value/functionality (in this case for mineral resources), the operational links between LCIA (Life Cycle Impact Assessment) indicators reflecting resource depletion/dissipation and quality recycling are also described. This approach is taken further in Beylot et al. (2021) where low-functional recycling is described as that where the recovered material provides such a low function compared to its potential functions and value that it is not a resource, attributing such reduction in functionality to the absence of technologically/economically feasible processes to recover the original function(s) and associated value of the resource in a given temporal perspective. In their predecessor review, Beylot et al. (2020) use the concept of functionality to define 'dissipative flows' of abiotic resources as "*flows to sinks or stocks that are not accessible to future users due to different constraints preventing humans to make use of the function(s) that the resources could have in the technosphere*".

Along these lines, Roithner and Rechberger (2020) propose a calculation of the recycling rate based on exergy and show how current EU recycling rates (as requested by European Commission, 2019) do not capture the quality of the recycled material and/or the functionality of the recycling process (i.e. the quantity of material that is "actually" useful for further use in the economy to displace virgin production). An explicit definition of quality is not provided, but implicitly the authors use the exergy content to distinguish between functional/non-functional recycling operations that are implicitly referred to as high/low-quality.

3. Possible avenues to define quality of recycling

As a red line throughout existing literature, we identify the following concepts and approaches, having in mind that they need to be valid for a different set of material resources.

3.1. Technical characteristics

The technical characteristics are the properties that give the material the ability to fulfil the required functions. For some material groups, including plastics, the content of impurities is connected to this (Faraca et al., 2019; Muchová & Eder, 2010; Pivnenko et al., 2014; Rodriguez Vietez et al., 2011; Villanueva & Eder, 2011). Nevertheless, while keeping the level of contaminants under a given threshold is clearly important, this is not necessarily sufficient to meet the requirements for a specific application. While impurities can be one reason for deficits in technical characteristics, also other reasons might cause this, such as fibre length reduction in paper or oxidation of materials. Additionally, next to technical characteristics, for some materials such as plastics processability is key (Demets et al., 2021; Eriksen et al., 2019).

3.2. Functionality and functional recycling

The work from Demets et al. (2021), Eriksen et al. (2019), Peiró et al. (2018), Rigamonti et al. (2020), UNEP (2011), Vadenbo et al. (2017) uses the concept of functionality of the recycled material as the main criterion to determine its quality. The functionality for a specific intended application is approximated with a bunch of selected technical characteristics. For example, Demets et al. (2021), Eriksen et al. (2019), and La Rosa et al. (2018) used mechanical and processability characteristics to derive the functionality of secondary plastics in a number of possible applications. Rigamonti et al. (2020) suggest instead the use of one representative functional characteristic per each combination of material-application for the sake of feasibility/simplicity of use in LCA, which is largely followed by recent studies (e.g. Ardolino et al., 2021; Cardamone et al., 2021). Accordingly, the agronomic nutrient-uptake-efficiency is the main function (once fulfilled thresholds on contaminants) to define the quality of waste-derived fertilisers (Huygens et al., 2019; Huygens & Saveyn, 2018; Tonini et al., 2019). The concept of functional recycling is at the core of the criticality methodology of the European Commission (Blengini et al., 2017), where only metals and materials that are functionally recycled contribute to mitigate the risk of supply disruptions.

3.3. Substitutability or suitability in manufacturing

Substitutability indicates to which extent the recycled material can provide the same function(s) of the primary material, thus their substitutability. In many LCA studies, the substitutability is approximated using the ratio between the market price of the secondary and the primary material (Mengarelli et al., 2017; Rigamonti et al., 2009; Schrijvers et al., 2016, 2020; Zampori et al., 2016). In others, the substitutability is quantified based on practical experiences in the recycling industry (Gu et al., 2017) or rather qualitative estimates (Shen et al., 2010). While this factor is important in LCA to quantify the benefits of a given recycling process, it often does not provide alone an indication on the quality. Notably, this could be the case when such factor is based on the ratio of the respective market prices, as these can be driven by short-term market fluctuations or corrections (e.g. tax, subsidies) with no direct relation to the technical material quality (see Rigamonti et al., 2020; Schrijvers et al., 2020; Schrijvers & Sonnemann, 2018). As discussed in Eriksen, Damgaard, et al. (2018), a waste polymer of potentially high-quality may be recycled into a low-quality product and be fully absorbed by the EU manufacturing market because of the high demand (EU market is far from being saturated; see Fellner & Lederer, 2020). In such case, a one-to-one replacement of the low-quality counterpart produced from virgin material resource would take place while nevertheless incurring a suboptimal recycling (quality loss or cascading). However, it can be argued that the ratio does reflect the quality of the recycled relative to the virgin material (for the intended application) when a rigorous comparison based on the key technical characteristics is made, as e.g. for plastics in Demets et al. (2021) or Eriksen et al. (2019).

3.4. Suitability in the CE

It may be argued that the suitability in the CE is very much related to the ability of preserving the functionality of the material, alongside fulfilling the market demands, i.e. end-of-life recycling rates should be sufficiently high (Eriksen, Damgaard, et al., 2018). A combination of quality and quantity recycled from a system should allow closing material loops. To operationalise this concept, starting from the substitution potential proposed by Vadenbo et al. (2017), Eriksen, Damgaard, et al. (2018) propose the circularity potential indicator. This indicates the extent to which the demand from the different market segments (e.g. of the wider plastic market) is satisfied by the recovery system in place, under a situation of market equilibrium. A debatable assumption of Eriksen, Damgaard, et al. (2018) is assuming that high-quality (plastic) recycling coincides with closed-loop of food-grade plastic packaging. One may question why other closed-loops, e.g. insulation-plastic recycling into new insulation-plastic, could not be similarly considered high-quality recycling. As an alternative approach, Grant et al. (2020) use a scoreboard to credit the recyclability potential (1-to-3; 1: capable of many recycling cycles, 2: limited recyclability and 3: unrecyclable), leaving this as an additional stand-alone dimension of quality. It is noticeable that from the case studies analysed by Grant et al. (2020), Eriksen, Damgaard, et al. (2018) and Demets et al. (2021), it appears that high recyclability potential nicely corresponds to preserving the material characteristics, which in turn tends to reflect closed-loop recycling.

3.5. Closed-loop and open-loop

Drawing upon the literature and the ongoing debates about the fate of recyclates (e.g. recycled plastic from beverages diverted to sectors other than beverages packaging), we observe that: I) a better definition of closed-loop appears desirable (e.g. for plastic market, is closed-loop bottle-to-bottle or bottle-to-food-packaging, or bottle-to-packaging?). II) The closed-loop/open-loop dichotomy makes rather sense in a context of linear economy, where loops are disconnected to each other. Yet, when the economy as a whole becomes circular, or is redesigned to be more circular, closed-loop concepts may need to be "enlarged" and open-loop can even become a more resource efficient option as stressed in the results of Andreasi Bassi et al. (2022) and Geyer et al. (2019). In fact, there might be cases where open-loop recycling produce recyclates of adequate quality for another application, rather than unnecessarily pushing closed-loop recycling processes to increase the technical properties of recyclates to meet the standards of their virgin counterpart. Open-loop recycling can still contribute to meet demand of the virgin resource while incurring environmental benefits as long as there is an unsaturated market application for that secondary material which is ready to absorb it (Andreasi Bassi et al., 2021, 2022). However, one should also bear in mind that these substitutions would not occur when such outlet markets suddenly become saturated (e.g. because of closed-loop recycling initiatives taking place within that sector or bans in export).

3.6. Links and integration of the concepts/approaches identified

Fig. 1a shows how the different concepts of quality, as used in the

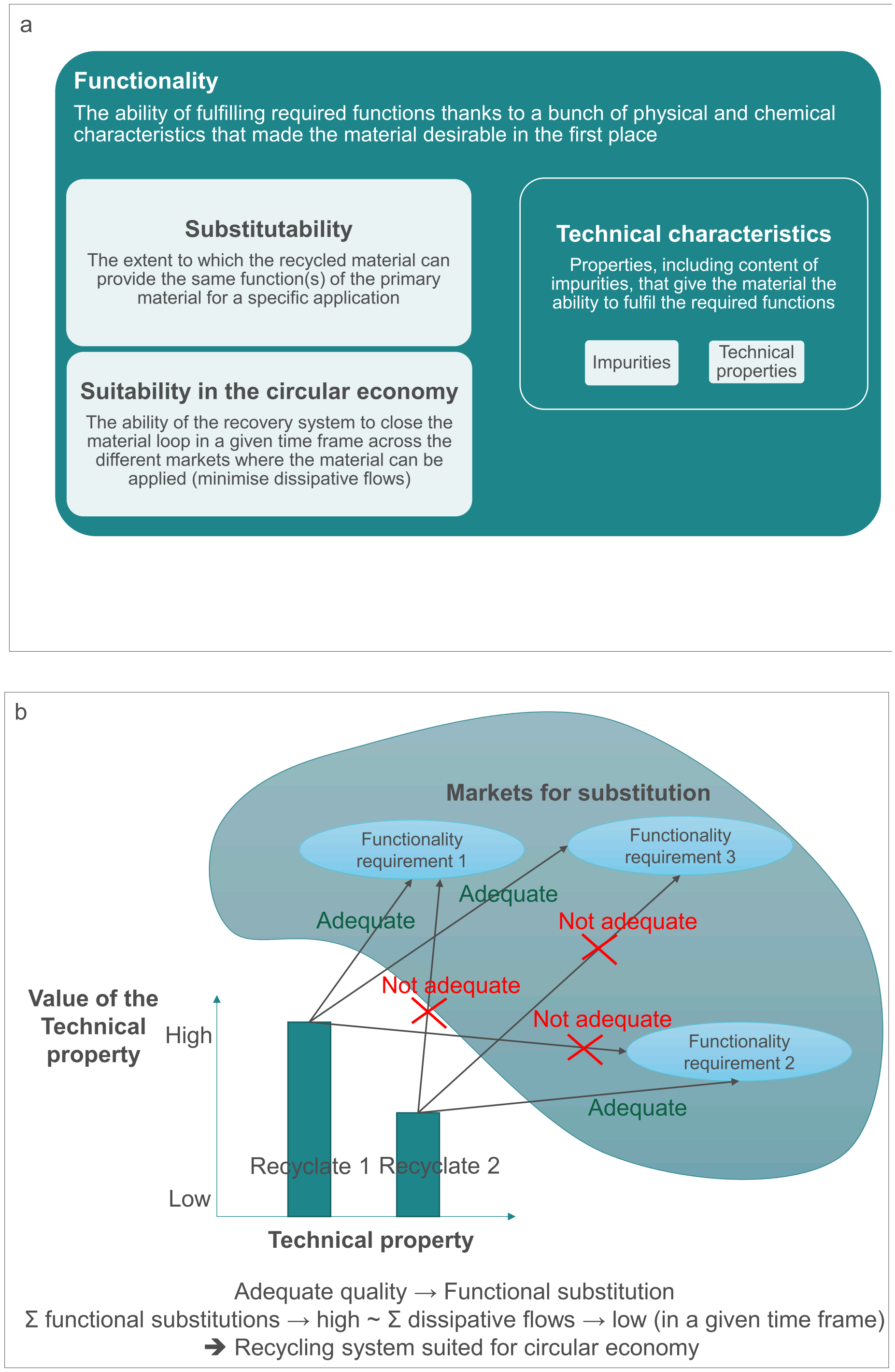

Fig. 1. a) Conceptualization of the criteria that should be part of a framework for the definition of quality of recycling based on the approaches available in the literature. b) Focus on the relationship between technical properties of a recycled material, which define its functionality, and the substitution of primary material across different markets where the material can be possibly applied.

studies identified in the literature, can be integrated to draft a framework for quality. Impurities are clearly part of the broader group of technical characteristics, and a bunch of these is typically essential to fulfil the desired functions of the intended material application. It can be argued that, based on properties, the quality of recycled materials will have to be 'adequate', regardless of the type of the intended application, else the manufacture sector would not uptake them (Fig. 1b). Precisely for this reason, at a system level preserving functionality becomes key as it allows achieving a maximum of substitutions across the multiple markets where the material can possibly be applied. Therefore, looking at material- or product-specific substitutability in view of the suitability for CE, is *per se* not sufficient. How materials with different qualities flow through the economic metabolism either within one application or over applications with different qualities is clearly crucial. Certain markets have well-established recycling systems largely maintaining technical characteristics, with high rates of recycling, and thus contribute significantly to bringing resources back in the economy towards functional substitutions, either in the same market or in another one. Whereas other sectors/material applications do not have a well-established recycling chain, and high amounts of impurities and/or loss of technical properties might occur, in worst case with low recycling rate, as such they are in a way 'sinks' for quality of recycling. Meaning, if materials end up in these applications they are most probably lost for many functional substitutions. This thinking holds over one recycling cycle, but also over longer periods of time. This reasoning is also very-well in line with approaches such as the MaTrace approach (Nakamura et al., 2014) and from a resource perspective, this in a way corresponds to minimising dissipative flows along the recovery system, with a maximum of functional recycling (Beylot et al., 2021; Ciacci et al., 2016; Graedel et al., 2011; Reck & Graedel, 2012; Stewart & Weidema, 2005). Yet, many of these resource-focused approaches are very broad and not very explicit on the material quality aspects and the potential of functional substitution based on the technical characteristics of the material resources.

4. The environmental dimension of quality of recycling

The approaches touched above do not tackle environmental impacts. A recycling producing high-quality recyclates may be associated with higher impacts than one with a lower quality output, due to energy/resource consumption or material losses. This is shown, for example, in Andreasi Bassi et al. (2022) for the case of PET-to-food grade versus PET-to-textile fibres, where the former results in comparable material recovery rates but different environmental impacts. Despite the uncertainty of LCA, it appears that the definition of quality of recycling should be complemented with additional criteria on the environmental performance. Referring generically to avoiding adverse effects, as in End-of-Waste criteria, seems leaving too much latitude for interpretation. This should however be carefully operationalised, as different approaches lead to different conclusions. An example is the following: a recyclate obtained from a chemical recycling process may result to be more impacting than the virgin counterpart when applying a product-oriented LCA (e.g. the EU product environmental footprint), which, while focusing on the product, neglects the alternative management fate of the waste from which the secondary material is obtained, e.g. incineration or landfilling or other recycling routes. This has been methodologically discussed in Tonini et al. (2021) where three end-of-life formulas are compared including that of the EU PEF (PEF and other end-of-life formulas do not account for the fact that waste as a feedstock is constrained, i.e. already managed/treated, and that additional demand for recycling thus incurs changes in ongoing landfilling/incineration/recycling pathways). However, the same chemical recycling can be superior to the waste management alternative otherwise occurring for *that* plastic waste (e.g. incineration), when applying a process-oriented LCA, which focuses on the waste (or material) valorisation process. The application of either perspective (product- vs process-) may thus lead to different conclusions regarding the environmental performance of recycling. Another issue is that an LCA generates multiple insights into the environmental performance resulting in a complete but not definitive outcome. Therefore, the discussion about linking quality with environmental sustainability is still far from over and further research is desirable.

5. Towards a definition of quality of recycling

This article does not aim to deliver 'the' final definition and operationalisation of quality of recycling. Yet, we encourage more research on this topic. More concretely, future works should include the following facts that follow out of our previous analysis: I) the quality of recycling is in many cases not an on/off criterion; it might be argued that the quality of the recycled material shall be 'adequate' to fulfil the required functionalities in the intended end-use market applications, in line with existing industrial standards (e.g. for paper and metals). Some studies move into this direction (Demets et al., 2021; Eriksen, Damgaard, et al., 2018), but it is clear that technical knowledge from the different material classes (metals, plastics, paper, etc.) needs to feed into this kind of work, especially for plastic for which standards on the quality of the recycled materials are lacking. II) While substitutability *per se* typically refers to the degree of substituting primary materials with secondary, the overall yield of the (recycling) value chain is also an asset of quality: how much can be substituted in how many markets. Notice that this goes beyond end-of-life recycling rates, as it involves the step of substitution. These elements are included in the formula of "substitution potential" by Vadenbo et al. (2017) and similarly in the "true recycling rate" by Klotz et al. (2022). We argue that if the sum of the 'functional substitutions' (across the different end-use markets where the material can be applied) is high enough, then the recovery system would be suitable in a CE perspective (Fig. 1b). This in turn corresponds to minimise the dissipative flows, i.e. emissions, disposal/incineration, low- and non-functional recycling of *that* resource after its use. Conversely, low-quality incurs a distinct loss in quantity and functions, allowing only a limited substitution at system-level (higher dissipation). III) Environmental analyses are an asset of the concept of quality of recycling, but their inclusion in the quality framework is challenging and needs further research.

The current EU *acquis*, while stressing that recycling shall be steered towards high-quality, does not provide an operational definition. Research in this direction is therefore key to support waste policies that maximise the benefits of recycling while fostering circular economy. The priority should be given to material resources, e.g. plastics, for which less industrial experience exists in defining common grades at EU and international levels.

6. Disclaimer

The views expressed in the article are the sole responsibility of the authors and in no way represent the view of the European Commission and its services.

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.

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