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**REVIEW PAPER** 



# Product Quality in the Circular Economy: A Systematic Review of its Definition and Contexts in Scientific Literature

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# Abstract

In the context of the Circular Economy (CE), quality is one of the most widely used keywords, but generally perceived as an ambiguous term without further definition or explanation. The present paper analyzes the use of the term product quality in the context of the CE through a systematic literature review including 132 peer-reviewed journal articles. The results reveal that the term quality, although not always explicitly defined, is associated with a variety of topics, namely market value, customer perspective, functionality, technical attributes, longevity, R-strategies and design, and environmental aspects. The aforementioned topics are used in different application contexts and partly show reciprocal relationships amongst each other. They further refer to the three sustainability perspectives (environmental, economic and social). The quantification of quality is observed to be rather limited and mainly based on assumptions. When it is quantified, technical properties, functionality and longevity are most frequently mentioned aspects, which are used within circularity or environmental impact assessment. While acknowledging the limitations arising from the scope of the included studies, which may be influenced by the keywords chosen, the review revealed that quality in the CE literature is complex and ambiguous. Therefore, for future research, we recommend authors to clearly define quality and its characteristics in the context of their respective research. By doing so, a better interpretation and comparability of the results can be achieved.

Keywords Circular Economy · Quality · Value · Recycling · Downcycling

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# Introduction

The transition of the current linear economy to a Circular Economy (CE) is a major step towards sustainability and long-term industrial competitiveness [1]. The CE concept aims at avoiding waste generation by keeping products and materials in the loop as long as possible, while using primarily regenerative resources and fostering restorative use of non-renewable resources [2]. Among other so-called R-strategies for the circulation of materials [3], recycling plays a central role in the CE concept and recycled materials are expected to comply with high quality requirements [1].

Nowadays, downcycling, i.e., the conversion of materials into materials of inferior quality or functionality [2], also referred to as "imperfection (...) in the product and material cycles" [4], is considered to be a common phenomenon [3]. However, such quality degradation constitutes a limiting factor to circularity [5]. Despite the seemingly common understanding of the term downcycling, the respective classification of real-world examples evokes controversy among experts [4]. Recycling of construction and demolition waste in road construction, for example, is partly considered as a valuable opportunity for waste reduction [6], whereas being described as undesired downcycling by Di Maria et al. [7]. This controversy makes it particularly interesting to further examine the term product and material quality. The latter is omnipresent in CE literature but at the same time difficult to define in a universal way [4]. Even though the term quality is frequently used in official regulations, e.g., in the European Circular Economy Action Plan [1], regulators do not explicitly define it in the CE context [8, 9].

In scientific literature, Helbig et al. [4] indicated a multitude of perspectives entering into the definition of product and material quality when defining downcycling. In one of the most relevant and current reviews tackling the quality definition, Tonini et al. [10] analyzed recycling quality mainly focusing on the technical perspective. Furthermore, Roosen et al. [11] introduced an operational framework for quantifying recycling quality encompassing three dimensions: displacement potential of virgin material, lifetime of stock in use and environmental impact. The present paper aimed to take a step forward by identifying quality definitions and related terms at a micro level in CE literature following a systematic approach. The focus in this regard is not on end-of-life (EoL) or recycling, but on all quality contexts within the CE.

Micro level assessment can be used for products, companies, consumers [12, 13], within this paper, we refer to micro level as product/material level, and throughout this paper we use the term product or material quality to indicate that the focus is on the micro level. It should be noted that the term 'material and product quality' in this paper covers primary material that is used for further production, secondary material that is available for further production after recycling, and any product that is either ready for the customer or any intermediate product ready for further production steps. However, in the analysis of the quality term, we did not specifically distinguish between products and materials.

The present article is structured as follows: Sect. 2 presents an overview of current scientific CE literature and briefly summarizes available quality definitions. Subsequently, Sect. 3 describes the method applied for answering the research questions, namely a systematic literature review (SLR) enabling a comprehensive overview to reflect the state of knowledge. The results of the review are presented and discussed in Sect. 4. Finally, a conclusion is drawn in Sect. 5.

# Background

CE research includes a variety of disciplines, thereof most frequently industrial ecology, production economics, operations research and waste management [14, 15]. Due to the novelty of the CE concept and its interconnections to other concepts, a variety of definitions exists. Nobre and Tavares [16] provided the following holistic definition of CE:

"Circular Economy is an economic system that targets zero waste and pollution throughout materials lifecycles, from environment extraction to industrial transformation, and to final consumers, applying to all involved ecosystems. Upon its lifetime end, materials return to either an industrial process or, in the case of a treated organic residual, safely back to the environment as in a natural regenerating cycle. It operates creating value at the macro, meso and micro levels and exploits to the fullest the sustainability nested concept. Used energy sources are clean and renewable. Resources use and consumption are efficient. Government agencies and responsible consumers play an active role in ensuring correct system longterm operation." (p.10).

Another widely accepted definition of CE is provided by Kirchherr et al. [17], who defined CE as "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers." (p.229). In a further review, Kirchherr et al. [18] evaluated the CE literature again and compared the outcomes with the previous review [17]. The authors concluded that the understanding of CE is more consolidated and differentiated. For example, sustainable development and CE enablers, which were rarely mentioned in the previous review, have been more strongly integrated into the CE definition [18].

However, the concept of CE and its sub-concepts are still being further developed [4]. Scientific literature already contains a multitude of literature review articles.<sup>1</sup> The majority of these reviews focuses on specific application cases or industries, only few articles tackle overarching topics such as the nexus between CE and sustainability [19–21], CE indicators and assessment methods [22, 23] and business models [24-28] or the concept itself, and its evolutions and approaches [17, 29–32]. However, the quality aspect and its role in CE have rarely been studied. One of the remarkable studies that becomes relevant in the context of the quality topic in CE is the study by Helbig et al. [4], which deals with the terminology of downcycling. The authors pointed out the lack of a definition of downcycling, which is generally associated with quality, and proposed the following definition: "Downcycling is the phenomenon of quality reduction of materials reprocessed from waste relative to their original quality, where waste means any substance or object which the holder discards or intends or is required to discard. Downcycled materials count as recycled materials. One can distinguish between thermodynamic, functional, and economic downcycling." (p. 1168). While doing that the authors also identified four main causes for downcycling, namely: dilution, contamination, lack of demand and design-induced [4]. In addition, the authors

<sup>&</sup>lt;sup>1</sup> A Scopus search conducted on 24.02.2023 with the search terms: Title-Abstract-Keywords: "Circular Economy" AND "Literature Review" resulted in 1,170 results in total.

mentioned that the thermodynamic effort of recycling, the functional use of secondary materials and the economic value of materials can be used to quantify CE progress. However, the lack of data, hampering quantification, is also mentioned as an obstacle. Besides Helbig et al. [4] who mainly focused on the downcycling terminology, Tonini et al. [10] identified main parameters that were used for quality of recycling from a technical point of view. The authors emphasize the importance of taking the technical properties of the recyclate into account, as they have an impact on the area of application and consequently on functionality. This becomes especially important within CE transition, as functionality is strongly linked to substitution potential, which is widely used in the environmental impact assessment of recycling systems. There are some studies that consider the quality aspect in LCA [7, 33, 34], however, the application of a wide range of approaches without transparent documentation and justification has also been reported, which can lead to misinterpretation of LCA results [35]. At this point, the framework proposed by Vadenbo et al. [36] is a good starting point for substitution modeling within LCA based on two main aspects: marketbased or technical functionality. However, further research is needed to investigate the link between technical functionality and product displacement in market-based approaches and uncertainty consideration. Furthermore, the study by Vadenbo et al. [36] serves more as a reporting framework while the quantification of substitution for different product groups requires the consideration of different aspects. With regard to the quantification of quality, the study by Roosen et al. [11] is noteworthy, in which a framework for the quantification of recycling quality is proposed. This study is an essential step towards a systematic and transparent approach to recycling quality quantification, building upon the framework proposed by Vadenbo et al. [36]. The authors proposed a comprehensive approach that includes in-use stock lifetime, environmental impact and virgin displacement potential as the main elements for quantifying recycling quality, where the potential for virgin material displacement is calculated as a function of technical suitability for substitution, end-of-life recycling rate and market weight, as well as taking into account economic boundary conditions [11].

Even though the quality topic within CE literature is getting more and more attention, to our knowledge, there have not been any articles giving an overview on the contexts that quality is used within CE literature. Thus, the present article takes a comprehensive approach analyzing the quality term in detail by reviewing in which contexts and term the quality is used within CE literature.

On the political or regulatory level, quality standards were on the one hand mentioned as a driving force for CE, while on the other hand, lacking knowledge of product and material quality is still mentioned as an obstacle to CE [1]. Nevertheless, CE regulations do not provide a distinct quality definition [37]. Outside the CE context, a quality definition is, for instance, provided in the quality management systems standard DIN EN ISO 9000:2015 [38], in which a general definition as "degree to which a set of inherent characteristics of an object fulfils the requirements" is given. A broad range of potentially relevant criteria for quality evaluation becomes evident when reading the definition of characteristics, such as "distinguishing feature(s)", which are divided into six groups in DIN EN ISO 9000:2015 [38]. Besides the general quality definition, DIN EN ISO 9000:2015 [38] also provides the following quality definition at product and service level: "[...] The quality of an organization's products and services is determined by the ability to satisfy customers and the intended or unintended impact on relevant parties. The quality of products and services includes not only their intended function and performance but also their perceived value and

benefit to the customer.". The latter definition indicates the importance of the social perspective within the quality definition as well as an interconnection between quality and value.

As previously mentioned, CE is a holistic concept that encompasses different dimensions (environmental, economic and social) at different levels (micro, meso and macro). Within the CE context, the term "quality" is often used, but is still a vague term that is rarely defined.

The present review thus aims at further investigating the quality term in the CE context following an SLR approach. More precisely, we addressed the following research questions (RQ):

RQ1: What is the role and definition of product and material quality (and its development throughout the product life cycle) in current scientific CE literature?

RQ2: How is quality considered in CE indicators on a micro level?

# Method

A literature review aims at critically evaluating existing documents on a specific topic [39]. In order to identify, evaluate and synthesize [40] the existing CE literature with regard to the research question outlined earlier in Sect. 1, a SLR was performed. Such review is characterized by its systematic, explicit, and reproducible approach and may be applied for describing and explaining current knowledge for professional practice or identifying the research gaps [40, 41]. SLRs are highly relevant and beneficial as they capture all relevant literature related to the research questions addressed and are conducted on the basis of a predefined protocol with explicit selection and rejection criteria. In this way, the completeness and fairness of the review is maximized, while the bias of the review is minimized [41].

The SLR process was performed considering insights from Fink [40] and Kitchenham [41], and for the reporting of selection process, PRISMA statement [42] was taken as reference. In the first step, the research questions were formulated which were previously mentioned in the Introduction. During the early-stage selection phase of the present SLR, a preliminary review on the literature reviews focusing on CE was performed. The aim of this preliminary review was not only to ensure the uniqueness of the planned SLR but also to provide an overview of current reviews in the CE context as well as their respective methodologies, such as search strategies and selected literature databases.

For reporting the review, PRISMA guideline for reporting systematic reviews [42] is taken as reference. Prior to the review, a research protocol was prepared, and all relevant information are summarized according to [42], in the following subsection.

#### Search Strategy and Selection Process

The article selection process was performed in four steps: identification, screening, eligibility and inclusion, and an overview of the SLR process is presented in Fig. 1. The steps for article identification are described in Section *Database and Keywords Selection*, whereas screening, eligibility and inclusion are explained in more detail in Section *Article Selection Process*.



Fig. 1 SLR selection process overview

# **Database and Keywords Selection**

The process of searching the literature includes the selection of the bibliographic database as well as the search terms [40]. The databases were selected by means of the overview of current reviews on CE and preliminary search trials conducted with different literature databases. Scopus and Web of Science were selected as they were found to be the two main databases covering the largest proportion of the literature, meaning that they contain the biggest number of articles relevant to the field, and are the two most frequently used databases identified in our preliminary review mentioned above.

The keyword selection was based on a preliminary search where various combinations of keywords were tested to find the optimum search string that covers the relevant articles while filtering out the articles with a completely different field of research. First, three main core topics were determined: CE, recycling, and quality. Recycling was selected as a core topic, as the focus of this study is material/product level quality and it seemed to be primarily discussed in recycling context. Furthermore, the preliminary search showed that including these keywords helped to significantly reduce the amount of non-relevant articles without CE focus, e.g., related to medicine and physics. In order to include other R-strategies, open-loop and closed-loop were also added. As CE is the core topic, it was decided to include this term in the *title* search. However, regarding recycling and quality, the search strings were rather entered in the *topic* (title or abstract or keywords) of the articles. Considering the connection between quality and value outlined in the quality definition in DIN EN ISO 9000:2015 [38], it was decided to include value as a keyword under the quality search string. To ensure the reliability of the included manuscripts, the scope was restricted to peer-reviewed journal articles [43] written in English. The search string and filtering criteria that were used are shown in Fig. 1.

# **Article Selection Process**

In order to enhance reliability, all steps for filtering and synthesizing articles were conducted by two researchers according to the research protocol that was prepared in advance to reduce the bias and increase the reliability of the study [40, 44]. A total of 1062 articles were extracted from the selected databases after the search carried out on 22 September 2021. The data is imported to Citavi software for further screening and two reviewers carried out the article selection independently of each other, and afterwards, the results were compared and discussed.

After removing duplicates, 634 articles were filtered based on their title, and then the articles that are out of the scope of the topic were excluded (n=61). In the second level filtering, 573 articles were assessed based on their abstract, and the ones that did not mention quality, value, business model or CE measures were excluded (n=280). In the third level, the articles that used quality or value without giving any explanation or its role within CE were excluded through the full-text screening (n=157). After the exclusion of 4 further articles, due to a lack of full text availability, 132 articles were finally selected for further analysis.

# **Data Extraction and Collection**

For the data collection, two researchers identified the terms and contexts observed in the selected papers separately and then discussed. Similar categories are merged together to provide a concise and clear overview, such as R-strategies and design. For data extraction, the software Citavi is mainly used, which allows to create categories, take notes and other relevant functions to create a clear structure for the terms and contexts identified in the studies under review. In addition, Excel is used as a supporting tool to export the created overview, which forms the basis for the results presentation.

# **Results and Discussion**

A bibliometric analysis was first conducted to capture the linkages between the selected literature by using VOSviewer - version 1.6.19 [45]. Following this, a content analysis of the selected literature was performed including a detailed overview on how quality was used or defined in the CE context.

In Fig. 2, a distribution overview on the publication year of the selected articles is presented. Even though no filter on the article publication year was set during the selection process, 2014 constitutes the first year of relevant publications. The majority of articles were published between 2019 (n=29) and 2021 (n=44).

# **Bibliometric Analysis**

In VOSviewer, three different analyses were selected for the present review, namely document-level citation, author keyword co-occurrence and journal co-occurrence analysis. The document-level citation analysis represents the citation relationship between selected articles. An overview is shown in Fig. 3, in which the lines indicate a citation between the articles. Since the remaining articles (n=64) had no connection to other selected articles in



Overview on the publication year of selected articles

Fig. 2 Overview of the article publication year distribution of selected articles



Fig. 3 Document-level citation analysis for selected articles. The lines represent a citation between the articles. The size of the circle indicates the number of citations, and the distance between articles shows their relatedness. VOSviewer web-version can be accessed here (https://tinyurl.com/2k36vypc)

terms of citation, i.e. were neither cited by any of the selected article nor cited any other selected articles, only 70 articles are covered in the overview. Bocken et al. [46], Linder et al. [47], Reike et al. [3] and Rosa et al. [48] were observed to have the most connections with selected articles.

In Fig. 4, an author keyword co-occurrence analysis is visualized covering the keywords that were mentioned at least 3 times. The most mentioned keywords observed to be circular economy (n=92), recycling (n=30), and sustainability (n=17).

In addition, a journal co-occurrence analysis was performed, including journals in which minimum two of the selected articles were published. As shown in Fig. 5, the majority of the articles were published in the Journal of Cleaner Production (n=26), followed by Resources, Conservation and Recycling (n=16) and Sustainability (n=16).

#### **Content Analysis**

#### Terms Associated with Quality

The findings during the content analysis were grouped into several superordinate themes, in which important streams of information were bundled together. Figure 6 provides an overview of the topics and terms, illustrating their main relationships and interdependencies. Life cycle thinking and the consideration of all three sustainability perspectives as well as standardization were found to be overarching ideas in relation to product quality and value in the context of CE. These ideas are considered inherent to the superordinate topics identified.

From the literature review, some key terms were observed to be widely used in quality definition or context within CE. Within these key terms, technical attributes, longevity, R-strategies and design as well as environmental aspects were identified as characteristics



Fig. 4 Overview on the author keyword co-occurrence analysis with a limit of at least 3 repetitions. The colors represent different clusters and the lines relatedness of the keywords. VOSviewer web-version can be accessed here (https://tinyurl.com/2exyapgx)



Fig. 5 Overview on the journal co-occurrence analysis including journals in which more than one of the selected articles were published. The colors represent different clusters and the lines relatedness of the journals. VOSviewer web-version can be accessed here (https://tinyurl.com/2ebcntsd)



**Fig. 6** Illustration of the main quality terms and contexts observed in the reviewed CE literature. (The overview requires careful interpretation, as the goal was to provide an outline that would help readers easily grasp the terms used; however, it does not mean that there are no other connections between each term, rather the strongest relationships are shown.)

of material quality. At the same time, all these characteristics are observed to influence the perceived product quality and functionality in the CE context. Besides functionality, market value respectively a market existence characterizes products [49, 50]. Market value or economic value was considered and applied as a component or indicator [51–53] of product or material quality, besides functional [12] or physical parameters [54]. Vice versa, product quality influences product value e.g., through technical attributes [55–57]. It should be

noted that a clear distinction between the terms that are presented in Fig. 6 is neither realistic nor logical, as they have a direct or indirect influence on each other. Therefore, the overview in Fig. 6 rather serves as an orientation to the reader and should be interpreted carefully, as it shows the key terms and the most important relationships observed in the present review.

The majority of authors associated quality with more than one key term, which are shown in Fig. 6. We also observed that R-strategies and design is the most frequently used key term when referring to quality; however, usually no clear definition is given. When it comes to quantifying quality, technical properties, functionality and longevity are the most commonly used parameters. In addition, attempts to quantify quality are mainly observed in the assessment of environmental impact or CE potential. Each term, its meaning and role in connection to product and material quality and its use in the reviewed literature is explained in detail in the following subsection.

# **Market Value**

#### **Product Value and Product Price**

The term value (creation) is often used in an economic, market-oriented context [58–60, 53, 61]. Baena-Moreno et al. [62] introduced the term 'commercial quality' influenced by physical characteristics which emphasizes the relationship between product quality and market value.

In a theory-based approach referring to classical economic literature e.g. Hayek [63]'s idea of prices as communication systems for demand and supply in a market, Linder et al. [47] highlighted the role of the market price as information carriers, e.g., regarding relative scarcity changes. However, potential market failure such as monopolies, regulatory measures, lacking externality inclusions [47] or the absence of a functioning market must be considered as a limitation when expressing product value through market prices [47, 51, 54]. On the other hand, market prices may internalize (functional) product features that are difficult to quantify independently [56], making product values exceed the sum of raw material values [64]. The latter shows the close connection from market value to the social value dimension, i.e. in this case the *customer perspective*.

In CE literature, product or material value often referred to market prices at different life cycle stages [65–67, 52, 68–72] or costs respectively combined perspectives aggregated as value added or profit [73, 47, 74–77] or in life cycle costing (LCC) [78]. Timing plays a central role in valuation and gains specific importance in CE context with multiple or extended use cycles for product and materials [49, 78]. The net present value (NPV), which acknowledges the time-value of money concept, hence arises also within different CE indicators or valuation contexts [79–82, 49]. An example for this is the Circular NPV proposed by Rodrigo-González et al. [82], an approach involving the aggregation of the NPVs of different parts and life cycles of a product to a total product value.

Due to its quality indicating function outlined earlier, market value was also used for allocation and substitution in LCA [83]. Similar approaches could be found in different CE indicators covering economic product value [56], such as the Circular Economy Index (CEI) developed by Di Maio et al. [84].

It should be noted that other value dimensions such as environmental, social or consumer-oriented values also play an important role in CE [85, 86]. These value dimensions will be further discussed in the following sections.

Following the CE definitions outlined in the *Background* Section , it is important to aggregate market value with environmental and societal value components to integrate externalities to obtain a holistic CE perspective. Examples of such combinations of value were observed in the context of eco-efficiency calculations, e.g., by Zhou et al. [87] with reference to DIN EN ISO 14045:2012 [88] or in the Eco Cost Value Ratio combining market value and eco-costs [89]. In the same vein, Thakker and Bakshi [90] employed an efficiency factor relating output market value to cost to society. Combined assessment approaches that aim to cover all levels of the sustainability dimensions could potentially play an important role from a regulatory perspective.

#### **Business Model Value Proposition**

CE transformation also concerns business models. Nussholz [75] highlighted that CE includes transforming linear value creation structures to ensure long-term economic benefits. Current linear business models, on the one hand, become a barrier towards CE, if they are based on fast production, e.g. in the fashion industry, with products ending up with low quality and no value to be captured and resold [91]. On the other hand, transformation of linear business models holds a great economic potential [91–94]. However, the requirements for new transformative business models are considered to be exhaustive since they should provide additional value compared to competitors while producing less ecological burdens [71] and being profitable for a company [67]. Ada et al. [95] highlighted that the redesign of production processes may not only reduce pollution and environmental impacts, but also enable a company to reach new value levels.

In their framework, Urbinati et al. [94] showed four generic approaches for CE implementation in business models. For the development of such business models, literature frequently referred to the Business Model Canvas by Osterwalder and Pigneur [96], e.g [97, 98].., extending its value creation focus. Circular business models' value creation targets beyond traditional stakeholder groups towards social and environmental value creation [58, 97–99], considering the entirety of society as stakeholder [58] i.e., businesses, communities and industries [100]. This underlines the interconnection between market, social and environmental perspective in a CE context. For the classification of circular business models, Rosa et al. [48] referred to the Sustainable Value Exchange Matrix which is developed by Morioka et al. [101]. Value proposition is a central aspect of business modelling [75] and describes the reason for customer's choice for a specific company [96, 97]. Through new circular business models, customer value proposition is substantially changed [102]. A detailed description of customer value proposition in a CE context was provided by [99].

#### Customer Perspective

#### Perceived Quality and Value

The product value ultimately defined by the customer [103], is determined by intrinsic as well as a relational or emotional characteristics [89, 104]. Expressing their expectation on

quality [71], product use and pleasure, customers attribute an individual value to a product or service which is referred to as Customer Perceived Value (CPV) [89]. The difference between the market price and the CPV is referred to as 'surplus value' indicating the desirability of an offer [71, 89]. In contrast to commodity products where price almost equals value, luxury products may show very high surplus values [71] and are cited as good examples for circularity incentivizing for loss prevention [105]. In the reverse case example, dropping food prices due to industrialization have led to a lower perceived value of food in society and an increase in waste and losses [106]. Product circularity also depends on endurance, i.e., the avoidance of physical, technical, aesthetic or social obsolescence [56]. Perceived value may be increased through design [71] and high-quality products [102].

Quality perception is not always based on functional attributes but often relates to superficial habits such as colours [107–109] and may also be influenced by ambiguity and vice versa [110]. Milios and Matsumoto [110] highlighted that perceived quality as well as perceived risk is finally influencing willingness to pay (WTP), which again highlights the nexus between social and economic perspective.

CPV can be contaminated, i.e., impacted by real or perceived changes in products' conditions [111]. Such contamination can either be positive if e.g., a product is worn by a celebrity or negative, which is often the case if previous product use causes a worse image leading to diminished appreciation and utilization of circular or secondary products [102, 111]. Currently, the social value dimension, i.e. perceived quality often constitutes a major barrier to CE implementation [111, 112], especially if lower prices for secondary products are mentally connected to inferior quality [110]. Fashion industry is stated to be vulnerable to contamination in CPV [100]. Wagner and Heinzel [100] pointed out that perceived value in the industry is driven by quality, performance, consumer effectiveness, i.e., the belief to support environmental protection by behaviour, as well as availability and economic risk which plays an important role for secondary products. However, overcoming barriers of social prejudices by changing customer awareness may take time [102], requires informing customers and is strongly influenced by cultural mindsets [99].

#### Ownership

CPV is not only influenced by quality perception, but also by the valuation of ownership, which is — especially for products potentially functioning as status symbol — more appreciated than functionality itself [98]. Traditional linear structures are often based on product possession [113]; whereas CE aims at valuing experience and functionality above ownership [114].

Value in use has already been recognized as an additional value dimension by early economic literature [47]. However, market value and value in use seem to be closely connected, as functionality is highlighted to be market oriented [66].

#### Certification

Customer perceived risk may be mitigated through certification [110], which increases CPV and perceived product quality. A survey amongst Swedish clients by Milios and Matsumoto [110] showed that trustful quality certification, especially by an industry association, would increase the willingness to purchase remanufactured auto parts, even though such certifica-

tion would not constitute the most important factor in the purchase decision. Nußholz et al. [74], Paletta et al. [109] and Hagelüken et al. [105] also presented product quality certification as potential solution for fostering CE progress both in terms of customer perceived quality but also for assuring certain quality levels for further treatment of waste streams to be used as secondary resources. As an example, for such quality certification efforts for CE, Nußholz et al. [74] mentioned two individual Danish companies having introduced national standards for product certification to foster demand for secondary products. A similar approach was shown by [115], in which the authors stated that the recyclers should be certified assuring the quality standards DIN EN ISO 9000:2015 [38] to achieve a reliable and functioning recycling system for tires. In this context, it also needs to be considered that CE standards will force companies to measure waste and trace its origins, which may then add value to companies [106].

#### Functionality

Functionality is a widely used term in CE, especially focusing on the loop systems and differentiation between recycling and downcycling [9, 70, 73, 116, 117]. Hahladakis and Iacovidou [118] defined quality as remaining functionality in the waste management industry. Similarly, Adams et al. [65] referred to value, quality, and functionality as downcycling indicators. The design perspective highlighted by Sauerwein et al. [119], which is also discussed in *R-strategies and design* subsection, indirectly refers to product functionality in the context of quality and high value. When it comes to the quality of secondary materials and their substitution potential, functionality is the aspect that is most often mentioned. For instance, Eriksen et al. [120] stated that material substitution through recycling not only depends on quantity but also the quality, which is defined as the ability to fulfill the functionality of substituted virgin material.

The importance of functionality within the value aspect was also highlighted. Even though value was mainly used in monetary context, the usual perception of value — as economic value — was criticized by many authors [3, 76, 81, 82, 97, 121, 122]. In the context of economic aspect, functionality includes future aspects such as demand and resource scarcity, which are essential in CE context, in contrast to price, which mainly reflects current market conditions. For instance, Urbinati et al. [94] stated that product value should be represented by the number of functional units in its lifetime rather than by the price, which aims to replace the "pay-per-own" with the "pay-per-use" approach. Similarly, Martins et al. [123] supported this idea by mentioning that customers will be the product users, not the owners. However, in this context, as discussed in the *Customer perspectivesection*, customer acceptance as part of the social dimension also needs to be taken into consideration.

Functionality itself was mainly defined as technical ability to perform a task or usefulness [82, 103]; however, there are other elements such as social, aesthetic, or economic that can be used in the functionality definition considering consumer needs [111]. Elzinga et al. [98] emphasized this from a customer perspective giving an example of luxury products, where the status symbols become more important than the functionality. However, especially in the CE context, for most products the functionality is strongly connected to value [78, 124], which is also reflected as economic value [66]. Within CE, both in recycling systems and reused materials, high quality materials were mentioned to maximize value by keeping their functionality [51, 125]. In addition, Moraga et al. [126] indicated functional and economic

value as a dimension of product quality. Furthermore, functional requirements were stated to be based on application types, which then affect the quality requirements [126, 127]. Functionality is a broad term that covers many relevant dimensions related to circular systems and is a core aspect within CE literature [10, 128, 129].

Overall, within reviewed studies, functionality was used especially as a quality indicator for environmental assessment of recycling systems within LCA. From a social perspective customer perceived quality is linked to the product functionality which.

#### **Technical Attributes**

Regarding product quality, technical attributes were mentioned as an indicator for assigning different quality levels. Some authors mentioned it as products' discernible characteristics [130], inherent and intrinsic material properties [51, 104], or technical requirements / properties [67, 131] as quality indicators. Some others stated the technical product properties a should be added to other value dimensions already outlined, namely economic, social, and environmental [12, 54, 122].

In general, product technical properties were widely used in quality and value retention context; however, specification of these technical properties and how they are linked to quality lacks in many studies. Within the reviewed studies, it was observed that studies focusing on plastic included a more concrete specification and quantification of quality based on technical properties compared to other product groups. Even not much observed as plastics, there were some studies on concrete/construction materials that also specified the technical properties as quality characteristics. In the following section, the technical properties for plastic and concrete/construction groups that were observed in the reviewed studies are further explained.

# Plastics

Some authors used specific technical properties of plastics for quality assessment, including interfacial tension [54], tensile strain [61, 132], intrinsic viscosity [133, 134], melt flow index [77, 133], and flexural/tensile modulus [5, 77, 132, 135, 136]. Some others mentioned mechanical properties, among other quality indicators such as color, odor, flammability or processing properties [5]. Hahladakis and Iacovidou [118] stated that the quality depends on the properties of the material, its designed characteristics, and the changes during their use, handling, and reprocessing.

Sanchez et al. [77] used a framework for technical quality characterization considering three major elements: structural and morphological feasibility of production and stability, and low molecular weight compounds, which considers chemical nature, macroscopic properties, and degradation products—impurities—, respectively. As there may be different technical parameters that can be relevant, consideration of all relevant parameters is important. A remarkable example of this is the study conducted by Eriksen et al. [120], in which different quality levels for plastics were defined depending on the field of application, as there are different parameters, such as physical and chemical, composition, mechanical strength, color, odor, additive concentration, and content of toxic chemicals, which can have different importance for different applications. In addition, the authors have not only considered the technical properties of plastics, but also the market situation for the circularity assessment and carried out a thorough evaluation.

Some authors used the technical properties for quality indicator calculation. Civancik-Uslu et al. [135], for instance, conducted a case study focusing on polypropylene and compared three different quality measurements within LCA following DIN EN ISO 14044:2020 [137], namely technical properties, price as well as composition and price. The authors concluded that technical properties — based on flexural modulus — constitute the most suitable approach for quality assessment. Following a different approach, Huysman et al. [54] defined four different compatibility classes, which are based on interfacial tension, and then also connected these compatibility classes to quality of plastics that will end up in four different waste treatment options: (1) closed-loop, (2) semi closed-loop, (3) open-loop, and (4) incineration. However, the range for different compatibility classes was set according to literature values for quality and mentioned that it requires further validation [54]. Nakamura and Kondo [138] highlighted the use of waste plastics for fueling cement kilns as an example of indirect substitution of primary materials caused by a lack of quality in recyclates.

# **Concrete / Construction Materials**

The studies focusing on concrete mentioned that the quality is related to strength of the concrete which is affected by water content, aggregate size, and aggregate expansion amount etc [139]... Similarly, Yu et al. [140] remarked the importance of the quality of recycled concrete aggregates and linked it to grading size, particle roughness and general cleanliness. From a different perspective, a study focusing on environmental potential of selective demolition, Melella et al. [57] highlighted the role of dimensional, performance, or aesthetic characteristics within value creation as enablers for reuse.

#### Other Product Groups

Quality within recycling was mentioned in various case studies in different fields, focusing on biogas and biodiesel production [62, 141, 142], mushroom crops [143], steel scrap [144], paper [107], textile [145, 146], and additive manufacturing [147]. For metals, Niero et al. [148] referred to the ILCD handbook for the quantification of quality downgrading of recycled metals, e.g., through quantification of inherent properties or the comparison of primary and secondary materials.

However, quantification of quality levels was not always reported. A complete reporting of how the quality levels were assigned and what assumptions were made is essential and should be provided in further research.

#### Longevity

Lifetime plays a central role in valuation and gains specific importance in CE context with multiple or extended use cycles for products and materials [49, 78]. During their life cycle stages, products incorporate different values [66, 72]. R-Strategies constitute enablers for longevity, furthermore, longevity is strongly connected to functionality as well. Shevchenko et al. [72] mentioned that "the circularity actually has no value in and of itself, but it does imply that a material provides value over a longer period of time". They referred to Frank-

lin-Johnson et al. [149], who introduced a new circularity indicator based on longevity as a value oriented and non-monetary approach. Franklin-Johnson et al. [149] highlighted the importance of longevity within CE and criticized current CE indicators for being based on resource use. To address this, the authors introduced a new indicator, the longevity indicator, capturing the time span that a resource has been in use, i.e., its initial lifetime as well as refurbished and recycled lifetime contributions and their respective probabilities [149].

Product quality was mentioned together with durability [56, 58, 150], which extends product lifetime. It is hence also closely connected to the functionality and R-strategies aspects.

#### R-Strategies & Design

Even though CE literature oftentimes referred to value as economic value [72, 81, 151, 152], value creation in CE contains four dimensions, namely smaller/faster cycles with less energy and resources, cycling for longer, cascaded uses and pure regenerative cycles exist [2, 5, 59, 121]. These cycles do not only refer to technical but also biological material cycles [51]. Hence, in CE value creation is closely connected to its retention [56, 70, 78, 104] and maximization [57] by extension [46, 153] and preservation [75]. However, the value term itself is often not defined in detail in such contexts [108, 154].

In contrast, the term product quality is defined as remaining quality in the context of waste management [118] or at least connected to functionality within cascading systems for distinguishing between up- and downcycling [9, 51, 73, 116, 117, 125]. From the reviewed articles, it was observed that product and material quality relating to R-strategies were used considering different life cycle stages. Therefore, it was decided to present them according to these phases, which are roughly referred to as product design, first product phase and second product phase, in the following section.

#### Product Design

CE already starts in the design phase of products. Concepts such as green products [155], design for deconstruction [74] or design for upgradability and adaptability [119] aim at extending product lifespan and increase EoL product quality and reduce costs of circular practices such as deconstruction [75]. Through proper product design, product quality can be improved, influenced by e.g., functionality and longevity, which are further discussed in subsections *Functionality* and *Longevity*. Loop optimization requires the integration of product design as well as business model innovation and reverse network management to reach CE goals [81].

Overall, it can be said that product design characterizes product quality [118] not only by enabling environmental and economic savings through lightweight product design [156] as well as technical and biological cycles [150], but also by creating customer product value inducing longer or more intensive product use [71].

#### Initial Product Quality

From a circularity perspective, initial product quality is especially important since it marks the root of further cascades [157]. In terms of value, cascading systems promote the impor-

tance of retained, residual or preserved value [46, 59, 60], which may also be expressed in terms of energy, labour and material [158]. EoL product value depends on available options and required efforts for further use, but also potential disposal costs [154]. Further processing can increase the value of the EoL product by utilizing it for further applications yet incurs additional costs [142]. In this vein, recyclability [113, 133, 153, 159, 160], ease of repair and disassembly [52, 56, 161], reusability [104, 156] or demountability for reuse [125] are characterizing product quality and product value in a CE context. Reusability, in turn, may besides functionality also depend on aesthetic characteristics [57].

# Secondary Product Quality

In terms of quality retention, the role of remanufacturing was particularly highlighted [55] since– according to British Standards Institute (8001:2017) [162]– remanufacturing exclusively guarantees at least equal product performance or quality compared to newly manufactured products [163].

If materials are to be recycled, purity of the input streams is mentioned to be a crucial factor for recycled product quality [164, 62, 133, 73, 118, 165–167, 117, 168, 148, 5, 169–171]. It determines whether recyclates can represent direct or indirect substitutes for primary materials [138]. Purity is not only the result of waste quality [51, 140], but is also determined by sorting and collection systems as well as recycling process itself [77, 99, 134, 138, 170, 172]. The role of recycling quality within CE was highlighted by many authors, and downcycling is stated to be a barrier for CE. A huge quantity of recycled materials is lost due to its low quality, and the stagnation of low-quality recycled materials cause a problem [115, 120, 173, 174]. In case required purity cannot be reached, three different types of contamination, namely technical, systemic and interaction contamination can be distinguished [111]. For the example of aluminium scrap, Niero et al. [148] remarked that its value is directly dependant on the contamination level.

#### **Comparison of Alternatives**

The multitude of CE strategies requires careful analysis of the best available options in terms of environmental performance and may require cross-sectional collaboration to find possibilities for industrial symbiosis to maintain value [112]. Related to recycling, literature often distinguished practices in up- and downcycling [140]. Here, the latter often relates to a loss in quality [70, 169]; however, the indicators of quality loss or its quantification tend to be undefined, and few of the articles reviewed specify the parameters for quality assessment, which are further discussed in the Section *Quality inclusion in the CE indicators*.

Tanguay et al. [157] outlined that the introduction of a quality indicator comparing newly manufactured and secondary quality has a strong impact in comparative LCA studies. An overview of similar approaches for measuring quality in material cycles was provided by Kral et al. [131]. Likewise, Sazdovski et al. [5] compared different allocation methods for considering quality in LCA taking the example of beverage cans. As this example shows, the lack of standardization in the field [169] may lead to big differences in LCA results.

#### Obstacles to High-Quality CE Practices

Product quality management is a key difficulty in CE implementation [95]. Currently, low quality product and waste quality are often considered to hinder high-quality CE as it makes additional process steps necessary and thus decreases profitability of recycling processes [164]. Since market prices do not necessarily cover costs [103, 105], EoL product values currently may also take negative values [175]. Furthermore, numerous authors highlighted that CE implementation currently lacks product quality certification [176] and standardization of products [177] and recycling processes [77] to ensure high-quality circulation. For quality assurance, CE transformation requires standards also on scrap level [144]. Experiences from industries with high product standardization levels have shown important reuse potentials [57] and could hence serve as role model for other industries. Similarly, Yu et al. [140] highlighted the importance of clear and strict waste classification which will lead increased quality of recycled material with reduced cost, as purity of construction and demolition waste will be reduced. The current calculation approaches on recycling systems were criticized, and some suggestions for a complete overview were presented. For instance, Aguilar-Hernandez et al. [178] suggested to use hybrid data tables including the waste stream in physical units (mass) and services in monetary values for on environmentally extended input-output analysis, rather than using purely market-based approaches. Similarly, Haupt and Hellweg [174] criticized the current recycling rate calculation, which is solely based on the collection rate that does not reflect any information on the efficiency of recycling system and quality of the recycled material.

Even though the importance of quality in CE was clearly stated by many authors, difficulties of assessing material quality was also mentioned, as it is based on multiple technical characteristics which are sometimes difficult to compare/combine [179]. Even though a comprehensive analysis covering all relevant aspects is essential, it is worth mentioning that the quality assessment for different products often can be time-consuming and challenging, as each product group is subject to different parameters, as stated by [120].

#### **Environmental Aspect**

Environmental value is mainly considered as a pillar of sustainability, in addition to economic and social value. Many authors referred to the connection between economic and environmental aspects [48, 51, 61, 69, 75, 149, 153, 180]. In the value creation and product value topics, terms such as eco-value [180], green value creation [76] and eco-efficient resource use [149] were observed to be used for combination of economic and environmental dimensions. Regarding the environmental value, i.e., the link between economic and environmental aspects, it is worth remarking that the consideration of externalities plays an essential role in reflecting the reality.

Criticising the current practices, Mikkilä et al. [81] stated that the economic value is the only value dimension that has been quantified so far. Unlike economic value, where e.g., accounting standards define value calculation [73], limited data availability constitutes a main challenge for quantifying environmental and social value [81]. From a customer perspective, Elzinga et al. [98] mentioned that through economic value creation for society, value proposition will be extended to environmental and social value creation. In CE and value creation, there are different views when it comes to the relation between sustainability

dimensions. For instance, Santagata et al. [181] mentioned that the "waste to resources" approach creates added value and simultaneously reduces environmental impacts. On the contrary, Stegmann et al. [122] stated that circular approaches are not always sustainable, and Sauerwein et al. [119] put emphasis on the differentiation of sustainable and circular practices. Sazdovski et al. [5] highlighted that environmental impact optimization requires knowledge on limitations of circularity due to quality degradation of materials.

Environmental quality and value were also studied as an indicator within CE. For instance, retained environmental value (REV), introduced by Haupt and Hellweg [174], compares the environmental impact of recycled/remanufactured product to original product. REV covers not only the value retention processes (such as recycling etc.) but also the use-phase and any changes that occur in the use-phase. The authors highlighted the importance of considering three pillars for sustainability within circularity assessment and mentioned that economic and social aspects should also be considered. Similarly, Steinmann et al. [9] introduced an indicator for the circularity of material quality ( $Q_c$ ) which is based on energy demand and the net energy demand of recycled products is compared to original one. In addition, LCA on recycling systems, the importance of quality aspect to differentiate downcycling and recycling was mentioned and studied [7]. Although LCAs for recycling systems are widely used, the quality of recycled products is rarely considered in LCAs. The latter is illustrated, for example, in a SLR focusing on LCA for recycling of construction and demolition waste by Bayram and Greiff [35], in which the authors present the current state of LCA studies and highlight the lack of inclusion of recycled material quality in LCA.

#### Quality Inclusion in the CE Indicators

In order to answer the RQ2, CE indicators and other assessment methods (e.g. LCA), within the selected literature were analyzed with regard to their approach towards product and material quality. Some authors explicitly stated and defined quality while using quality as a parameter for circularity indicators, which are explained in detail in this section.

Within LCA, Civancik-Uslu et al. [135] included recycled material quality in three different ways, based on technical, price, and a combination of price and composition. The authors concluded that a quality factor based on technical properties (in the case study defined as flexural modulus of wood sheet) reflects the reality better than market price. Similarly, Tanguay et al. [157] emphasized the importance of considering quality in LCA of recycling systems and concluded that the inclusion of quality changes the results by up to 15% in attributional LCA and by over 97% in consequential LCA. Quality factors were determined based on market values or inherent characteristics; however, the suitability and identification of quality factors was noted to be outside the scope of the study and suggested for further studies to undertake [157].

Considering environmental aspects, Haupt and Hellweg [174] introduced a new indicator, retained environmental value (REV), to quantify environmental value retention. Product quality is considered in terms of the type and quantity of primary material displaced, taking into account functional equivalence, available quantities and market preferences. Authors also highlighted the need for further research focusing on economic and social aspects to be included in CE indicators [174]. Steinmann et al. [9] proposed circularity of material quality (Qc), which is an energy-based indicator and calculated as the ratio of recycled to primary material. In the calculation of Qc, possible losses and dilution (as wt.-%) were considered. Charnley et al. [130] defined a new indicator called certainty of product quality (CPQ) which is a function of physical condition, part remanufacturing history, part replacement history and data from sensors, following a weigted approach. The authors mentioned that "if the remanufacturer was certain/confident about the quality of the returned product, the CPO value would be between 0.8 and 1.0. If the remanufacturer was uncertain, the number would be between 0.1 and 0.5". However, the suitability and certainity of the assumed values are critical. Schaubroeck et al. [49] introduced a framework for sustainability assessment of CE. Even though the aforementioned authors emphasized the importance of material quality, no explicit definition of quality was mentioned, and it was stated that "various quality parameters could be considered, but here we just present quality in general" (p.6). Eriksen et al. [120] assessed the circularity potential of plastic packaging considering the quality aspect. The authors defined quality based on various aspects covering such as physical and chemical composition, mechanical strength, color, odor, additive concentration, and content of toxic chemicals. Focusing on plastic packaging, this quality assessment and its inclusion in CE assessment, we think that this is a well-defined and comprehensive approach; however, it is data- and time-intensive. Huysman et al. [54] introduced CE performance indicator for post plastic waste considering quality aspect. The authors used a technical property-based quality assessment, i.e., interfacial tension. In total, four different compatibility classes were defined, and the quality was calculated as a function of the mass percentage of the added polymer.

In general, quantifying quality as a function of CE indicator is a complex issue that requires further research. Through this review, we identified three main challenges of using quality within CE indicators. Firstly, quality indicators are specific to each individual product group as the relevant parameters change based on the product group, thus, a generalized indicator could not be used. Secondly, the fact that quality is a broad concept encompassing different aspects: economic, technical, environmental etc., covering all the relevant aspects requires data and it can be a time-intensive process. Lastly, when it comes to the quantification of quality, the risk of double counting should be considered as relevant parameters from different dimensions are not totally independent from each other. In align with this aspect, also the weighting of the various parameters in the quantification of quality as an end-point value poses a challenge.

# In-Depth Discussion and Synthesis with Existing Research Findings

In this section, a deeper discussion is presented by summarizing the findings observed in this review. In addition, the research findings are synthesized together with relevant research on quality in CE. A summary of the research findings is summarized in Table 1, covering the explanations and barriers. In the articles reviewed, the term quality is frequently used in the context of R-strategies, especially when distinguishing between recycling and downcycling, however, a definition of quality was rarely provided. When considering longevity in the CE context, quality tends to be mentioned in terms of durability and there is limited focus on this aspect. On the contrary, market value was also mostly mentioned in connection with quality in the articles reviewed, particularly in the assessment of the various sustainability dimensions (economic and environmental) and the assessment of the CE. Although the use of market value as a quality indicator is quite straightforward and understandable, it is also criticized as the monetary value does not always reflect quality and is volatile. The customer

Terms and	Explanation and barriers
contexts	$(\rightarrow)$ (-)
Market Value	<ul> <li>Product value and product price</li> <li>→ "Commercial quality" is used to reflect the relationship between product quality and market value.</li> <li>→ The material value is referred to as the market price in the LCC and CE indicators.</li> <li>→ Market price is used as an indicator of product quality for allocation and substitution in LCA.</li> <li>Business Model Value Proposition</li> <li>→ Value creation through business models, value is generally used as an economic aspect, but sometimes also associated with quality.</li> <li>→ On the one hand, business models have great potential for the creation of high-quality products within CE, on the other hand, linear business models become an obstacle for CE, e.g. the stagnation of low-quality materials in the fashion industry.</li> <li>Market prices are volatile and do not reflect externalities.</li> <li>Market prices are volatile and do not reflect materials.</li> <li>Market prices are volatile and do not reflect externalities.</li> <li>Warket prices are volatile and do not reflect externalities.</li> <li>Warket prices are volatile and do not reflect externalities.</li> <li>Warket prices are volatile and do not reflect externalities.</li> <li>Market prices are volatile and do not reflect externalities.</li> <li>Warket prices are volatile and do not reflect externalities.</li> <li>Market prices are volatile and do not reflect externalities.</li> <li>Market prices are volatile and do not reflect externalities.</li> <li>Market prices are volatile and do not reflect externalities.</li> <li>Market prices are volatile and do not reflect is externalities.</li> <li>Market prices are volatile and be not reflect externalities.</li> <li>Market prices are volatile and be not reflect externalities.</li> <li>Market prices are volatile and be not reflect externalities.</li> <li>Market prices are volatile and be not reflect externalities.</li> <li>Market prices are volatile and be not reflect externalities.</li> </ul>
Customer perspective	aspect, neglecting the CE transition. Perceived quality and value $\rightarrow$ Customer defines the product value/quality, which is individual and can be related to intrinsic, relational, and emotional characteristics. $\rightarrow$ CPV and WTP are concepts which are used to refer to the perceived quality from a customer perspective. <i>Ownership</i> $\rightarrow$ Ownership has a strong influence on CPV, especially for products that are seen as status symbols. <i>Certification</i>
	<ul> <li>→ Product quality certification is essential to gaining trust of customers thus fostering CE progress, especially for recycled materials.</li> <li>Lower prices for secondary products are mentally associated with inferior quality.</li> <li>The perceived value and quality are individual and vary from person to person.</li> <li>Ownership within traditional linear structures becomes an obstacle to CE transitions as product quality or value is strongly associated with product possession.</li> </ul>
Functionality	<ul> <li>→ Functionality is widely used within CE context, especially for loop systems to differentiate recycling and downcycling.</li> <li>→ Especially for the substitution within LCA, functionality of secondary materials is used as an indicator for quality.</li> <li>→ Also, for economic value, it is highlighted to put more focus on functionality for the products by replacing the "pay-per-own" with the "pay-per-use" concept.</li> <li>→ Functionality is mainly referred to technical ability to perform a task or usefulness, however, the term itself can be related to social, aesthetic, or economic aspects.</li> <li>Even though mainly used in a technical context, social and aesthetic properties can also be considered as functionality.</li> <li>Quantification is challenging (e.g. in LCA) and mostly done based on assumptions.</li> <li>Quantification of quality through functionality involves different parameters for different product groups and may cover various aspects, such as different technical parameter and market demand, which makes the quantification complex and data</li> </ul>

 Table 1
 Summary of the terms and contexts for quality within CE covering a concise explanation and barriers observed within the reviewed papers

Table I (commucu
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$\rightarrow$ )(-) $\rightarrow$ For the quality assessment, technical attributes are used as indicators and param-
$\rightarrow$ For the quality assessment, technical attributes are used as indicators and param-
1 2 1
eters, representing the most tangible application in this review.
$\rightarrow$ Within LCA, widely used for quantification of quality and strongly connected to
functionality.
$\rightarrow$ The majority of the studies referring technical attributes for quality indicator are
Different parameters are relevant for different product groups, making possible standardization challenging.
Intensive data requirement and selection of relevant parameters are the main challenges.
→ Within CE assessment, longevity plays an essential role and is widely connected with R-Strategies and functionality.
$\rightarrow$ Quality is mostly mentioned within durability aspect which plays an essential role for assessing longevity.
$\rightarrow$ Longevity as a CE indicator, introduced as a value-oriented and non-monetary approach, captures the time span in which a resource is used.
Mostly assumptions-based estimation on the lifetime, and the indicators for durabil- ty & quality are not documented transparently.
Currently, there is a limited consideration of longevity within CE assessment.
$\rightarrow$ One of the most used key terms for quality within CE, covering both primary and secondary material quality.
$\rightarrow$ In comparative LCAs, especially for recycling systems, integration of quality in substitution is essential.
Quality is mainly used in the context of R-strategies but rarely defined. For recycling rate calculations, lack of consideration of material quality is criticized. Importance of quality in the CE context is highlighted, however the challenge of quantification of quality is also mentioned in the reviewed articles. Furthermore, a detailed and complete analysis requires data and time.
$\rightarrow$ The environmental aspect is mainly used in combination of economic value (e.g. eco-value, green value creation).
$\rightarrow$ There are new approaches being introduced within environmental aspect, in which quality of materials are considered (such as REV and Qc).
Quantification of quality within LCA is an ongoing discussion topic that requires nore research.
Current LCA studies that include quality within LCA are mainly assumptions based. Different parameters become relevant for different product groups when quantifying quality, also different aspects become relevant (such as technical attributes, market situation, legal boundaries etc.), which makes the quantification complex and data ntensive.

perceived quality is rather individual and can encompass various aspects, such as intrinsic or emotional. To promote the CE transition, ownership is mainly seen as a barrier and certification as a means to gain customer confidence. With regard to the social dimension, it should be noted that some relevant aspects such as equity and quality of life were not observed in the articles reviewed. We acknowledge this limitation, which could be due to the choice of keywords. However, at the micro level, where the focus is on materials or products, the social dimension is rarely considered, which is also emphasized by previous studies [18, 182], although, as shown by Kirchherr et al. [18], the number of studies considering the social dimension is increasing, whereby the environmental and economic dimensions are still predominant over the social one. When it comes to explicit definition and quantification of quality, functionality is a widely used term. Similarly, the technical properties of products and materials are closely linked to functionality. For instance, when quality indicators are used in LCA, quantification is generally done by considering functionality, which is determined based on the technical characteristics of the product in question. However, market value as quality indicator or assumption-based quality parameters are also used in LCAs, as the lack of data is one of the main obstacles to conducting a thorough assessment that includes all relevant technical parameters for quantifying quality. In environmental assessment, the issue of quality has been discussed not only in the context of LCA, but also in the CE indicators. The main focus in this context is on the secondary product and its quality compared to the primary product. As mentioned previously, two remarkable examples indicators that were introduced are Qc [9] and REV [174], both of which take similar approaches in terms of the relative impact of the recycled material compared to the primary material being replaced by the recycled material.

When considering the comparison of the results of the present study with relevant previous research in the field of quality in the context of CE, two studies dealing with the quality of recycling [4, 10] provide a relevant synthesis of the results. In the review focusing on quality of recycling performed by Tonini et al. [10], the authors emphasized the lack of quality definitions in scientific studies focusing with recycling and concluded that in defining the quality of recycling, the technical properties of recyclates are essential, together with functionality, which reflects whether and to what extent the recyclate finds an end use. In addition, the authors noted a link between functionality and substitution in relation to environmental assessment in the CE context. The authors also indicated that there is a need for further research concerning a quality framework for the environmental assessment of recycling systems [10]. In the present study, we came to a similar conclusion when it comes to recycling and the quality of secondary materials, although the study was broader in scope and not limited to recycling. Based on the present review, it was found that in the environmental assessment of recycling systems, technical properties and functionality are two key terms used as quality parameters and/or indicators. However, detailed information and how the quantification of quality was carried out are rarely documented. Within the reviewed articles, a good example is the study by Eriksen et al. [120], in which a comprehensive assessment of quality quantification considering technical characteristics and market situation was conducted, although the authors also acknowledged the challenge of high data requirements and time-consuming assessment for such a detailed analysis. Within the topic of downcycling, a relevant study performed by Helbig et al. [4], which focuses on the terminology and the authors introduce three types of downcycling: thermodynamic, functional, and economic downcycling. The focus of the study is again on the recycling stage, and impurities, dilution, lack of demand or design-related downcycling are identified as possible causes for the reduction in material quality. Even though the scope of the study differs slightly between Tonini et al. [10] and Helbig et al. [4], both identify technical properties, functionality, and the market situation as the main factors for the quality of recycling or downcycling.

The quantification of quality is a particularly relevant topic in LCA, and there is an ongoing discussion, especially with regard to substitution approaches for recycled materials. There are some relevant studies that provided guidance for substitution in LCA, in which quality aspect becomes relevant. For instance, framework developed by Vadenbo et

al. [36], is a remarkable example, from which further research can be built upon. In a recent study Roosen et al. [11] introduced a framework to quantify quality of recycling, which is calculated using three dimensions: virgin displacement potential, in-use stock lifetime and environmental impacts. While doing that, for the virgin displacement potential, the authors build upon the framework introduced by Vadenbo et al. [36], in which the specific focus is on substitution in LCA. For the technical suitability for the substitution (which is used as a function in virgin displacement potential), mechanical properties, processability, aesthetics properties, chemical load and legal boundaries are stated. At this point, the relevance of different indicators may vary depending on the product group in question. In addition, the legal limits are not always reflected by the technical characteristics and the permissibility varies from country to country. At this point, relevant aspects for quality quantification could be selected depending on the product group with justification and transparent documentation. Although there is an ongoing discussion and efforts in LCA requires further research.

# Conclusion

The present literature review showed a close connection and interdependency between the terms of product and material quality and value in current scientific CE literature. Although this study provides a comprehensive overview of the definition of product quality in the CE context, there are some limitations of this study. The literature search covers only peer-reviewed, English-language journal articles; therefore, some relevant gray literature that could fit within the scope of the study was not included. With regard to the social dimensions of sustainability in the context of CE, we recognize the potential limitation of this review, which may be caused by the choice of keywords. Nevertheless, it is worth noting that, especially at the micro level, research on social dimensions is rather limited compared to environmental and economic aspects. Hence, the elaboration of additional social factors in relation to product and material quality could constitute an avenue for further research.

With regard to the first research question, it can be stated that the terms quality and value are discussed in a large variety of contexts which are partly interdependent. We observed that functionality is a key term mostly used as an indicator of quality, and that market value is a parameter strongly influenced by product quality. On the other hand, technical characteristics, longevity, R-strategies and design, and environmental aspects are generally used to characterize product quality.

Through this review, we observed that no uniform definition of the terms exists and that the particularities of the respective application contexts of products and materials should be considered, which was also pointed out by Helbig et al. [4] and Tonini et al. [10]. Another interesting finding was that the reviewed articles rarely refer to quality standards or provide explicit definitions of the quality definition on which their analyses are based.

Regarding the second research question, quality inclusion and its quantification in CE indicators was observed to be limited and mostly based on assumptions instead of justified calculations.

Hence, in further research, studies with specific targets on individual product groups could be useful to define specific quality elements and provide approaches for their reliable quantification. Although some studies have introduced quality factors to be used in LCA studies in particular, the quantification of quality factors and parameters considered is rather based on assumptions and is a research topic that should be further investigated. Since CE is a holistic concept that encompasses different aspects and levels, a common understanding of CE would be helpful to achieve consistency. At this point, it should be noted that standardization of CE, especially when it comes to CE measures and indicators, plays an important role. As far as CE standardization is concerned, ISO/TC 323 covers various aspects that have been partially completed or are currently in progress. Besides standardization, the scientific community creates great potential through the further development and conceptualization of CE, where clear statements and documentation are essential.

Additionally, it can be concluded that the social perspective, more specifically the customer perspective, which is already part of the DIN EN ISO 9000:2015 [38], is and will be of special importance in the CE context. The perceived value perspective plays a central role for the successful transition towards a CE as customer acceptance finally determines product acceptance in a free market along the product life cycle. However, besides acceptance, the findings of the literature highlight the necessity for market prices to reflect to include environmental and social impacts and enable holistic decision making.

The multitude of criteria which appears both in the DIN EN ISO 9000:2015 [38] quality definition as well as in the findings of the literature review also indicate a central problem for universal quality standardization and certification. If the latter aims at increasing customer acceptance, the certificate itself needs to be accepted. However, if the diversity of quality criteria for different contexts requires a multitude of different certificates, the latter may decrease simplicity and hence customer acceptance. Criteria for standardization as well as the weighting of different quality criteria in certificates and assessments could hence constitute avenues for further research.

All in all, the review has shown that the quality term has a multifaceted definition in a CE context which needs to be specified in the respective application context while still providing numerous areas for further research as of now. The quantification of quality is a current topic of discussion and is gaining importance with the increasing attention on the transition to CE. Although a standardized definition and quantification framework may be challenging and not applicable, we strongly recommend that authors clearly define quality in their respective research and transparently document and justify the selected quality parameters and indicators. A further review has shown that quality in the context of CE requires a comprehensive analysis covering various aspects, which can be data-intensive and time-consuming. At the same time, the multitude of dimensions to be considered underlines the importance of interdisciplinary collaboration in research as well as other relevant actors, such as policy makers and standardization bodies.

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# Declarations

Ethics Approval Not applicable.

Consent for Publication Not applicable.

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