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Original Research

Circular Materials Under Analysis: A Systematic Literature Review and a Taxonomic Analysis of Circular Materials, Between Theory and Application

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Abstract: This contribution deepens the Circular Materials (CM) concept taxonomy, aiming to highlight the complexity and multidisciplinary nature of this argument and outlining its broader implications. The present study adopts the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) model to conduct a systematic literature review inquiring about the significant overlaps and divergences in CM definitions across disciplines on a sample of forty-one interdisciplinary works. Through a qualitative content analysis to systematically collect data for each work, this article delves into a taxonomy analysis of issues related to CM development, concerning concepts, terms, and key relationships around four complementary areas of interest. The taxonomy analysis is based on a holistic approach that intertwines various aspects (technical, economic, social), and it serves as a reference point for academics, policymakers, and professionals working to enhance and improve CM across various sectors and disciplines. This taxonomy provides a structured framework to (1) identify opportunities to improve recovery and reuse practices, (2) understand the interactions between the CM system features, and (3) support the design and planning of circular economy strategies in experimental settings as well as at industrial and policy levels. As a main finding, the CM material category proposal is established, underscoring the importance of a holistic approach to enhance the scalability and implementation of such materials across diverse contexts. Further studies can try to deepen the spectrum of references adopted in both academic and applicative fields, identifying, for example, metrics to align the priorities of the different disciplines or between industrial sectors to be more easily standardized in circular manufacturing processes.

Keywords: *Systematic Literature Review, Taxonomy Analysis, Circular Materials, Circular Economy, Circular Design*

Introduction

The exacerbation of the human ecological influence, generated by a linear economic system anthropocentrically based, has become an urgent contemporary concern (Papanek 1984; Del Curto et al. 2015; Thackara 2016). This linear model, characterized by the extraction, consumption, and disposal of resources, has led to environmental degradation, resource depletion, and unsustainable production and consumption practices. In 2015, Europe undertook a call for a cross-sectoral transition toward a more sustainable development, resulting in the publication of *Transforming Our World: The 2030 Agenda for Sustainable Development* (United Nations General Assembly 2015) an ambitious plan aimed at stimulating actions in areas of critical importance. This framework aims to address the interconnected dimensions of social equity, economic growth, and environmental aspects, prompting a cross-sectoral transition toward more sustainable pathways. Building on this foundation, the European Commission launched the *Circular Economy Action Plan* in 2020, a comprehensive initiative targeting the integration of circularity into economic and development models. The Circular Economy (CE) paradigm pursuit from the European Commission implies a shift from the linear material and energy exploitation toward the maintenance of value through symbiotic exchange. Circularity is seen as a key driver for limiting the human impact on the planet to a level that nature can tolerate. The CE model challenges traditional production methods, advocating for the regeneration of economic values, the elimination of environmental harm, and the creation of societal benefits (MacArthur 2013). At its core, a closed-loop system fosters a balance between environmental, productive, and economic systems, prioritizing the recovery and reuse of materials while respecting natural and technical reproduction rates. By respecting technical and natural reproduction and recovery rates, the circularity of resources could be pursued to mitigate ecological impacts of products and industries through the recovery of materials at the end of their life cycle and substituting as much as possible critical materials with renewable, low-impact alternatives (Braungart and McDonough 2013).

The present contribution covers the area of interest concerning Circular Materials (CM) from a design standpoint. CM are interpreted in the article as an umbrella term representing an interdisciplinary material approach to deal with the design of sustainable matter, influenced by technical, economic, technological, political, and social dimensions (Pellizzari and Genovesi 2021). These materials span diverse value chains, offering competitive advantages while dealing with adoption challenges in various application sectors (Cleries et al. 2021; Dumée 2022).

Despite their potential, the theoretical debate lacks a unified definition of CM, with the rise of divergent interpretations that increase the transition challenges. This fragmentation obstructs development efforts, knowledge transfer, and interdisciplinary collaboration between experts, limiting the scalability and integration of CM practices.

A design lens is assumed to act as a connecting means between interdisciplinary fragmented knowledge (Friedman 2001), integrating models of learning and development toward responsible and conscious decision-making processes (Buchanan 2001). Particular attention is given to the sub-discipline of Material Design, which explores materials from a multilayered perspective.

Goal of the Study

This study aims to deepen the understanding of CM by exploring their contextual variations and outlining their inherently complex and interdisciplinary nature. By addressing the fragmented definitions and practices associated with CM, the research seeks to establish a coherent and unified framework that aligns theoretical concepts with practical applications. The research is guided by two core questions:

1. What are the most significant overlaps and divergences in CM definitions across disciplines?
2. How do these differences influence research alignment and industrial applications?

By formulating an unambiguous and interdisciplinary taxonomy to be applicable in the academic context and potentially to bridge it within the practical application field, the contribution looks forward to enable a shared dialogue between the stakeholders of the circular system. This clarity will promote a more fluid dialogue between the disciplines and fields involved, nurturing transdisciplinary creative thinking in the field of Materials Design research. A key objective is to leverage the material design as a unifying lens to bridge the knowledge gaps and facilitate interdisciplinary collaboration, integrating multiple perspective dimensions and enabling a more aware and informed decision-making process.

First, the article delves into a systematic literature analysis to compare and merge semantic codes related to the CM concept, breaking down, sorting, and categorizing the terminologies associated. To synthesize and analyze the literature, a qualitative content analysis approach was employed. This method enabled the identification of recurring themes, concepts, and patterns across the selected studies. Taxonomic analysis was then applied to systematically classify and organize the findings into four primary areas of interest. Furthermore, the analysis deepens these areas, concluding with reflections and recommendations about the research applicability and future study directions.

Materials and Methods

To address the research questions effectively, a systematic literature review was conducted, aiming to consolidate existing knowledge and identify critical gaps related to CM within the CE. This review was guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) model, which ensures a structured, transparent, and replicable methodology (Moher et al. 2009). The PRISMA model has been widely adopted in the scientific debate, which provides a systematic and rigorous approach to research.

Through keywords cited by expert authors in the Material Design research field (Table 1), an initial retrieval allowed the collection of a total of 691 resources on the Scopus database. A rank screening was performed to include the most cited and recent records in the analysis, selecting 100 resources to review in detail based on their pertinence to the research questions.

By applying inclusion and exclusion criteria, a total of forty-one documents were chosen for qualitative inquiry via content analysis (Figure 1).

Findings are classified through a taxonomic analysis that focuses on linguistic and disciplinary variants—including distinctions in terminologies related to circularity—and concludes with recommendations for further study directions.

The PRISMA Model

The PRISMA model flow adopted in this study follows a four-step sequence (Moher et al. 2009) (Figure 1).

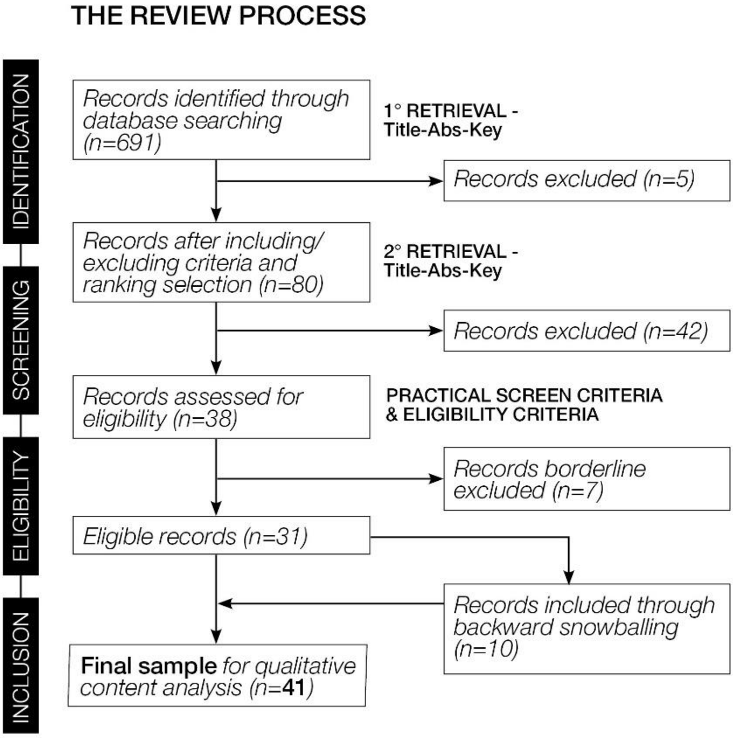

Figure 1: The PRISMA Methodology Adopted

1) Identification. To include key concepts related to CM and their design within the field of material design, fundamental keywords such as "circular," "materials," and "design" were selected, alongside variants depicted by the literature (Table 1). The systematic analysis conducted on the Scopus platform and performed between September 2023 and May 2024 resulted in a collection of 691 documents.

Table 1: Keyword Sets

Search Stage	*Keywords Set*
Initial retrieval	"circular* materials AND circular* design AND sustainable materials AND business scalability AND circular economy AND (environmental OR social OR economic OR ecological) AND (assessment OR evaluation OR analysis).
Second retrieval	"circular* material design AND (waste OR by-product* OR sustainabl* OR recyc* OR upcycl* OR biobas* OR regenerat* OR refurbish* OR reus* OR remanufactur* OR repurpos* OR re-min*)."

2) Screening. A citation-based metric, focused on the most highly cited publications, was used to include works with the highest impact in the scientific domain, as these are often considered reliable and influential by experts across disciplines. Simultaneously, a metric based on the most recent publications was employed to capture more direct connections with current trends and emerging micro-trends. For the initial screening, a ranking based on the number of citations per publication was applied, ensuring that the first set of analyses included the most relevant and widely recognized sources in the current scientific landscape. This phase resulted in a collection of eighty works, making the analysis more manageable yet sufficiently comprehensive. Additionally, twenty recent publications were included based on their pertinence, despite having fewer citations (last site visit on May 15, 2024). Altogether, one hundred works were selected for the subsequent analysis.

3) Eligibility. This study adopted various eligibility criteria to identify the most suitable research works, including:

- A temporal frame for including only research originating around and after the launch of the SDGs in the European governmental framework, in 2015, and the Circular Economy Action Plan (CEAP) implementation into the European agenda to assess the political influence on the scientific debate, examining practices, models, trends, and theories in material development toward circular orientation.
- Peer-reviewed research for ensuring the scientific credibility of the document consulted, together with accessibility criteria.
- The content focus on CM and related research, with sufficient information about the systems under analysis.
- Inclusion of diverse industrial sectors and material categories to evaluate scalability and impact, thereby allowing generalization of terminologies.
- Inclusion of interdisciplinary theoretical approaches and practices resulting in both qualitative and/or quantitative studies highlighting circular impacts.

Duplicate entries and works failing to meet these criteria were removed. By applying these filters, a total of forty-eight documents were excluded. The remaining records were further examined by reviewing titles, keywords, and abstracts. The resources included in the analysis provided descriptions of CM and closed-loop systems, detailed criteria for assessing benefits and challenges, and concrete examples of CM developments. This step led to exclusion of further works and the identification of seven borderline studies deemed insufficiently aligned with the investigation.

4) Inclusion. The snowballing technique, particularly the backward searching, was employed to enrich the sample of articles under analysis through cross-referencing the bibliographies of already included studies (Wohlin et al. 2022). By examining the reference lists of the thirty-one documents remaining after the eligibility criteria application, the introspective snowballing search allowed us to identify key works previously overlooked. Eligible criteria were not applied to this bunch of works. These additional references formed the basis for further exploration within the research field. Ten other additional references were identified, bringing the final sample to forty-one documents. These were subjected to a qualitative content analysis, using Excel to systematically collect data for each work.

Methodological Rigor

To enhance the reliability and validity of the findings, the following measures were taken. First of all, the research incorporated multiple disciplinary perspectives, triangulating the information sources to capture the multifaceted nature of CM. Moreover, the continuous refinement of the consulted works list based on the snowballing process allows for including domain experts and emerging trends in CE and MD research. This methodology provides a robust foundation for understanding the complexities of CM and their potential. Future studies could include additional databases and experts' interviews.

Limitations

The PRISMA method allowed to significantly reduce the final selection of consulted documents that may result in the exclusion of potentially relevant studies (e.g., less cited but with a high innovative potential). Additionally, the research could be enriched by expanding the data source through a diverse range of databases, including insights from policy and standard regulative documentations, for example.

Results

Research Trends and Contributions

According to the initial set of identified records, the analysis reveals a significant growth in CM-related research since 2015, with 164 works published by 2023. This reflects and aligns with the Sustainable Development Goals (SDGs) launch (United Nations General Assembly 2015), highlighting the impact of global sustainability agendas and policy frameworks into the scientific debate. Funding programs like Horizon 2020 have further supported and shaped knowledge advances and research priorities, emphasizing circular-related studies.

The circular discourse spans multiple disciplines, reflecting its inherent interdisciplinary nature, with remarkable contributions from environmental science (21.5%), engineering (16.8%), energy (13%), social sciences (9.4%), computer science (7%), and material science (6.6%). Such crossing diffusion highlights the CE complex challenges and the need for cross-collaboration and cross-approaches to address them. Most significant publication rates concern a limited pool of scientific journals, including *Sustainability Switzerland*—the most profitable, with a significant peak of twenty-eight circular-related publications in 2022—while the *Resources Conservation and Recycling*, *Journal of Cleaner Production*, *Procedia CIRP*, and *IOP Conference Series: Earth and Environmental Science* are other top contributors. The European countries confirm their position as research leaders around the circular debate, advancing and enriching existing knowledge through academic research. Specifically, the United Kingdom and Italian studies dominate the research landscape, resulting in the most successful productivity in terms of the number of works published, with 88 and 87 works, respectively, followed by Germany and Spain (66 each), the Netherlands (63), the Scandinavian countries (Sweden with 35 works and Denmark with 32), France (28), and Portugal (28). The strong representation of European countries underscores the alignment between research priorities and European sustainability policies. As relevant contributors, the United States ranks third with sixty-seven publications, indicating its active role in parallel with the European advancements.

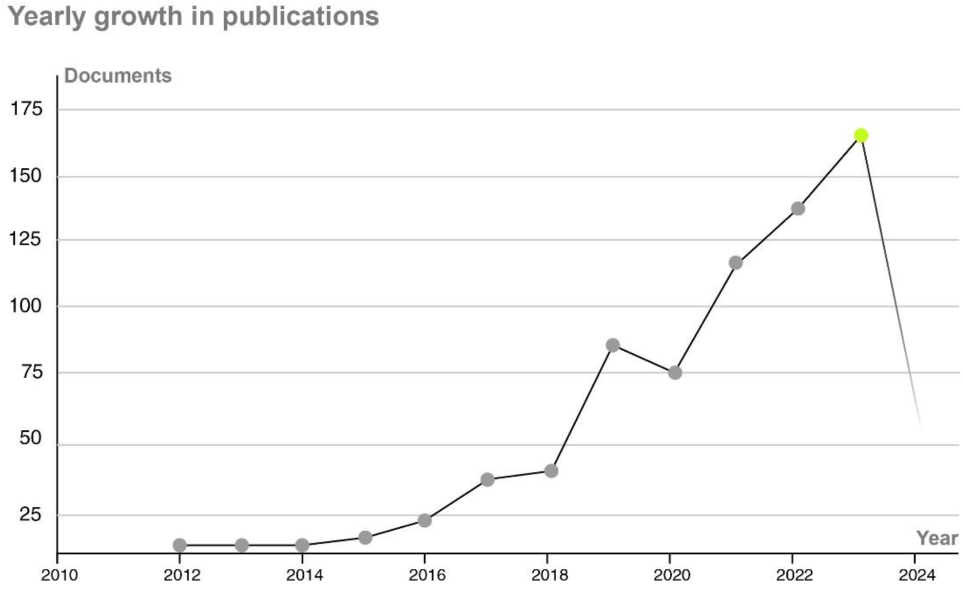

Figure 2: Yearly Growth in Publications Concerning CM-Related Research

Taxonomy Analysis

The study delves into the systematic classification of issues related to CM development through a taxonomy analysis of their concepts, terms, and key relationships. The critical review of the final sample of works enabled the synthesis of the CM-related topics around four complementary areas of interest, including:

- CM typologies: definitions and categorizations of materials based on their compatibility with circular flows.
- Circular flows: dynamics of material reuse, recycling, and regeneration across biological and technical cycles.
- Recovery strategies: methods and approaches for enhancing material value retention.
- Market challenges: barriers to the large-scale adoption of CM and potential solutions.

Each area engages with multiple taxonomic variables (Table 2 [first column]), displaying key points that emerged from the literature's content analysis (second column). These variables were cross-referenced with the research questions to ensure comprehensive coverage and alignment with the study's objectives. The key points represent the overall topics and resources covered by referenced authors (third column). Moreover, they could be assumed to be guidelines for distinguishing the taxonomic variables among the scientific and applicative sectors supporting the CM development. The taxonomy analysis is based on a holistic approach that intertwines various aspects (technical, economic, social), and it serves as a reference point for academics, policymakers, and professionals working to enhance and improve CM across various sectors and disciplines. This taxonomy provides a structured framework to (1) identify opportunities to improve recovery and reuse practices, (2) understand the interactions between the CM system features, and (3) support the design and planning of CE strategies in experimental settings as well as at industrial and policy levels.

Table 2: Taxonomy Analysis

Taxonomy Key Variables	*Definition/ Key Points*	*Further Readings Key References*
Circular Material (a)	Materials from waste and secondary recovered resources are designed to be compatible with biocycle or technocycle, aiming at substituting primary resources; Through open- or closed-loop systems, circular resources remain in the productive systems at their highest value as much as possible; They often provide rebound effects and require infrastructure, economic, and social changes to be fully implemented at the industrial scale; Core of CE strategies; Includes carbon-negative materials capable of sequestering and storing carbon (carbon balance); Solid, liquid, and gaseous raw resources from recovering processes generate directly into a unique component or indirectly from composite mix and production processes.	Reuter 2011; De los Rios and Charnley 2017; Dumée 2022; Hubmann and van Maaren 2022; Hubmann and Van Maaren 2022

Secondary Materials (SM) (a)	Materials from recycling processes, with potential contamination; Materials compatible with recycling technologies (e.g., metals, papers, glasses, plastics); Materials with high circular potentials; Materials with positive economic value (net value gain); Deliverable/output of recovery/refurbishing processes (from waste) that can be returned for like previous or new usage, with similar or reduced functions (the physical potential depends on the waste characterization); Substitute and/or temporary materials (e.g., aluminum and wood); Do not assure a stable supply chain (seasonal chemical and physical changes in material composition and properties); Changes in primary production or virgin material availability can induce SM demand to increase; Ingoing and outgoing materials (recycled and recyclable, respectively).	Allacker et al. 2014; Vadenbo et al. 2016; Helander et al. 2019; Cobo et al. 2018; Hahladakis and Iacovidou 2018; Hahladakis and Iacovidou 2019; Helander et al. 2019; Iacovidou et al. 2019; Pauliuk et al. 2021; Bolognesi et al. 2021; Kulczycka et al. 2024; Rotondi et al. 2024
Recovered materials (a)	Recyclates: Waste with an economic value can be turned into recyclates safely. Alternative materials that are recycled and/or recovered; Materials that increase their economic and environmental benefits based on recycling/reuse degree (circular degree) (e.g., low for recycling materials, medium-low for material reuse, high for building reuse); From waste (both pre- and post-consumer); Recovering processes may require raw virgin resources (e.g., PHA extraction/production needs absorbent materials for nourishing micro-organisms that transform nourishment into new materials); Their substitutive capability (to virgin counterparts) depends on available quantity, quality, and performative skills.	Reuter 2011; Vadenbo et al. 2016; Helander et al. 2019; Malmqvist et al. 2018; Eberhardt et al. 2019; Iacovidou et al. 2019; Eriksen et al. 2020; Mannina et al. 2021; Fishman et al. 2021; Eriksen et al. 2019; Hubmann and van Maaren 2022;
Secondary raw resources (a)	Waste (e.g., urban mining waste); Recycled materials' source (e.g., slag chemistry); Waste that can be turned into valuable recovered resources (e.g., water, energy, sludges); The waste quality strongly influences their recovery and transformation in SM (quality is a complex issue); The quality of recycled materials affects the quality of the secondary raw material (e.g., contaminations from additives for degradant stimulation in the waste material composition); Better recycling capabilities allow for quality growth of secondary resources from mixed waste; Reconversion of waste or by-products into new resources allows for land (stock spaces), biodiversity, and energy saving.	Reuter 2011; Allacker et al. 2014; Vogtlander et al. 2017; Mohammed et al. 2018; Iacovidou et al. 2019; Eriksen et al. 2020; Mannina et al. 2021; Florez et al. 2024; Aliotta et al. 2024; Rotondi et al. 2024
Primary materials (a)	From natural virgin sources (e.g., metals, concrete, copper, and plastics); For the market supply, equal quantities of primary and SM cannot be compared (e.g., 1 kg P not equal to 1 kg S even if calculated 1 = 1 in Life Cycle Assessment (LCA) assessment). Due to different seasonal chemical composition/physical properties, nut can be substituted with alternatives that provide similar or equal or higher performances (e.g., SM, easy to disassemble or recycle); The virgin material extraction is the input element for the footprint calculation; resources with pure quality (in comparison).	Allacker et al. 2014; Niero et al. 2017; Cobo et al. 2018; Hahladakis and Iacovidou 2018; Helander et al. 2019; Eberhardt et al. 2019
Primary detritus (a)	(Polymeric) debris in its original (product) forms (e.g., cigarettes, bottle stoppers).	Rhodes 2018

Secondary detritus (a)	Micro-size debris from the disintegration of primary debris (e.g., microplastics).	Rhodes 2018; Florez et al. 2024
End-of-life products (a)	Secondary source of materials with high embedded energy value but difficult to be recycled (mostly mixed composites) due to heterogeneous composition, hindering recovery processes to redesign their value	Froelich et al. 2007; Allacker et al. 2014
Material's Biosphere Compatibility (b)	Materials that can degrade, turning into organic nourishment for ecosystems, or at least degrade without damage to human and environmental health; intrinsic and designed properties.	Moreno et al. 2016; Geldermans 2016; Rotondi et al. 2024
Material's Technosphere compatibility (b)	Synthetic or inorganic materials that can be recovered and used without property loss; designed property.	Moreno et al. 2016; Geldermans 2016
Open-loop cycle (b/c)	Materials are cycled back a limited number of times; Mechanical recycling process that might reduce the material quality (material downgrade) due to chemical/physical degradation of matter, allowing the material to be used for lower-quality applications (e.g., PET bottles, construction materials); Downcycling—Downstream due to a cascade approach/logic from higher- to lower-grade application (e.g., textile recycling); Final transformation into waste; Economic value and durability loss; Regenerative processes (often involving third-party companies); Through low-quality recovery options, many materials can be recycled into new applications (e.g., pneumatics); Secondary (downgrading), tertiary (de-polymerization), and quaternary (energy recovery) recycling types.	Bocken et al. 2016; Cobo et al. 2018; Hahladakis and Iacovidou 2019; Iacovidou et al. 2019; Eberhardt et al. 2019; Campbell-Johnston et al. 2020; Dumée 2022; Kulczycka et al. 2024
Narrowing cycle (b/c)	Efficient usage of resources.	Bocken et al. 2016; Jørgensen and Pedersen 2018; Campbell-Johnston et al. 2020
Slowing cycle (b/c)	Designing durability and the lifespan extension of products, including disassembly.	Bocken et al. 2016; Jørgensen and Pedersen, 2018; Campbell-Johnston et al. 2020
Closed-loop cycle (b/c)	Mechanical recycling process that maintains similar or equal material quality compared to the original product, allowing to use it as a substitute or alternative to virgin counterparts; Upcycling is concerned, by contrast, with the downward value of substances recovered through retaining the material's high value (used repeatedly); Need accurate material information (e.g., availability, supply chains); Requires advanced recovering technologies (e.g., pyrolysis for biochar production) and the enhancement of remanufactured and reuse practices; Circularity of the material flow lasts for a certain period, then it turns into an open flow due to material degradation (e.g., glass bottle); It may involve a symbiotic exchange with other businesses; Designing for compatibility with technological and biological cycles; Primary recycling type.	Lyle 1994; Bocken et al. 2016; Sara et al. 2017; Cobo et al. 2018; Bukhari et al. 2018; Jørgensen and Pedersen 2018; Hahladakis and Iacovidou 2019; Iacovidou et al. 2019; Eriksen et al. 2020; Campbell-Johnston et al. 2020; Bolognesi et al. 2021; Hubmann and van Maaren 2022; Hubmann and Van Maaren 2022

Material circularity (c)	Focuses on the material quality besides the traditional calculation (e.g., involving the mass-based recycling rate and substituting rate); Depends on the quantity and quality of waste resources and their capability to fit, as a substitute, the original material's functions; Cradle-to-cradle approach.	Vadenbo et al. 2016; Despeisse et al. 2017; Bassi and Dias 2019; Eriksen et al. 2019
Circular Potential (c)	Replacing Substitutive Potential intended as measurement equation of the final usage change depending on the supply and market use (different from the Substitutive function that represents the functional performative equivalence); Adaptable and flexible solutions (through the substitutive potential) to support the decisional process; Depends on the crossing of inherent and relational material's properties; Function of the efficiency of the resource recovery system (Nrec) and market share (MS), where materials with specific quality levels (Q) have the potential to be applied to replace virgin materials; Framework that determines the technical functionality as well as the organizational, legal, social, economic, and environmental feasibility, describing the mine typology (e.g., separated streams, abandoned infrastructure, incinerator residues).	Vadenbo et al. 2016; Geldermans 2016; Eriksen et al. 2019; Kulczycka et al. 2024
Regenerate materials and products (c)	Materials flow that turns in the environment with zero or regenerative output (emissions)—footprint calculation; the regeneration process highly influences the material's embedded energy and environmental impact; Lower concerns for the environment compared to critical raw virgin material extraction (e.g., metals and rare minerals); Higher intrinsic value than second-hand (less risk and better quality) for consumers, but lower high-value perception compared with new products results in a misconception of the perceived value; Regeneration should focus on consumer benefits to lower the potential/perceived risks (e.g., increasing services like take-back programs); Companies may prefer to penetrate low-cost markets or promptly promote their brand reputation; Lower eco-costs due to less virgin raw material usage.	Lyle 1994; Vogtlander et al. 2017; Han et al. 2017; Helander et al. 2019; Mannina et al. 2021; Rotondi et al. 2024
Material Banks (c)	Temporary material stock in/for constructions and buildings; relational property.	Geldermans 2016; Hubmann and van Maaren 2022
Circular supply chains (c)	Pre- and post-consumer waste manufacturers; Pre-consumer or post-industrial waste (e.g., by-products) provides a more reliable supply chain in terms of quality, geographical availability, and seasonality; In Europe, they are mostly small- to medium-sized entities (polymer sector) that can generally supply companies small-size productions; The increase in the demand for circular/SM allowed the circular chains' growth (with better quality and quantity stability); Circular material manufacturing companies are strongly linked to the local territories.	Froelich et al. 2007; Sara et al. 2017; Han et al. 2017; Dumée 2022; Bos et al. 2024

R-strategies (c)	Designing for circularity, adopting a cradle-to-cradle approach from the reduction of resources to the extension of products and services' lifespan (e.g., through 10 Rs practices), and aiming at maintaining products and materials at their highest quality as much as possible.	Lyle 1994; Reuter 2011; Allacker et al. 2014; Geldermans 2016; Dalhammar 2016; Jørgensen and Pedersen 2018; Bassi and Dias 2019; Florez et al. 2024; Kulczycka et al. 2024;
Circular Design (c)	Redesign practices are influenced by economic resources (pursued by companies with higher incomes) and lower applicability due to lack of an implementation framework. Involves designing long-lasting products, can be disassembled, and can be easily recovered and reused or recycled; Identification of unused materials from technical or natural flows, transforming them into circular material alternatives; Drive small-scale changes by choosing materials that can be effectively recaptured, reprocessed, or safely returned to natural systems; Circular Thinking; The design of circular systems involves designing for X (e.g., for recycling, durability, resource efficiency, recovery, upcycling, processes, dissemble-ability); Though making practices and innovative niches mostly benefit from and progress circular resources, many barriers still remain to make them reliable at the socio-technical level; Design is interconnected with contextual factors (e.g., technical, legal, organizational, and cultural aspects).	Geldermans 2016; Dalhammar 2016; Han et al. 2017; Helander et al. 2019; Bassi and Dias 2019; Dumée 2022; Hubmann and van Maaren 2022; Hubmann and Van Maaren 2022; Ogunmakinde et al. 2022; Kulczycka et al. 2024; Aliotta et al. 2024
Circular business strategy (c)	Win–win strategy; It could aim at slowing, narrowing, and closing the material value streams.	Rizos et al. 2016; Campbell-Johnston et al. 2020; Bocken et al. 2016; Bos et al. 2024
Industrial symbiosis (c)	Industrial ecology inspired by nature, expressing the complex interactions between the material system's stakeholders; the industrial network for resource recovery and exchange; and business changes and reorientation as a circular enabler for companies' economic growth while reducing their environmental impact and innovating their market offer.	Lyle 1994; Reuter 2011; Jørgensen and Pedersen 2018; Garcés-Ayerbe et al. 2019; Mannina et al. 2021; Dumée 2022; Rotondi et al. 2024
Material value retention (c)	Part of the circular indicator focus; Experimentation for the secondary life of waste.	Corona et al. 2019; Dervishaj and Gudmundsson 2024; Florez et al. 2024; Kulczycka et al. 2024; Rotondi et al. 2024
Circular rebound effects (d)	Decadence of the scrap's material qualities due to its combination/dilution with mixed substances that enable its recovery (e.g., copper); Social, economic, and environmental implications need to be assessed and measured; Circular economic incentives (e.g., taxes) can prompt new technological advancements and material innovation without necessarily involving a reduction of waste generation; The regeneration of materials/products might involve cannibalization of sales; Regenerative processes are more expensive (human labor) compared to mass production and do not guarantee	Froelich et al. 2007; Dalhammar 2016; Rizos et al. 2016; Vogtlander et al. 2017; Cobo et al. 2018; Mohammed et al. 2018; Campbell-Johnston et al. 2020; Mannina et al. 2021; Dumée 2022; Bos

	good environmental performance (e.g., Regenerating an old refrigerator is less sustainable than purchasing newest due to the high energy demand); Closed-loop materials flow turns into open after a certain point; Circular material flow may engage unknown mixed substances in the material compositions (with harmful chemicals or polluting substances); Existing recovery technologies are not compatible or not already ready/commercialized for mass production (e.g., rubber vulcanization); Difficulties for local manufacturers to access circular supply chains compatible with their production size; The Extended Product Responsibility (EPR) regulation enables better recycling performance without reducing the consumption pattern. Misconception in social perception derived from a lack of information for an informed decision-making process; In Europe, circular suppliers are mostly small- to medium-sized entities (polymer sector) that cannot provide enough resources for sectoral companies (automotive), according to their quality and quantity requests; The more composite the circular material is, the more complex is its recovery process (e.g., sorting) with a lower percentage of material value recovered.	et al. 2024; Florez et al. 2024
Eco-costs (d)	Magnitude of the environmental load based on load prevention (costs that would have to be incurred to dispose of these materials according to the Earth's capacity to absorb them), also referred to as external costs in environmental economics.	Vogtlander et al. 2017; Helander et al. 2019
Circular niche (d)	Micro and small artisanal enterprises working in product niches within local contexts; they can scale up toward mass production through tailored sales (e.g., maximizing the project flexibility), relying on more stable circular supply chains (post-industrial waste, like pre-consumer); Local manufacturers have a (presumable) extended knowledge regarding the local resources and know-how; Novel niche and bulk applications occur within cascade recovery processes.	Castell et al. 2008; Payne 2011; Dalhammar 2016; Rizos et al. 2016; Sara et al. 2017; Han et al. 2017; Campbell-Johnston et al. 2020; Mannina et al. 2021; Dumée 2022; Bos et al. 2024; Rotondi et al. 2024

Discussion

The findings of this study provide a clearer understanding of CM and their potential(s). By adopting a taxonomic approach, the research highlights the critical interdisciplinary overlaps and divergences in CM definitions, revealing the complexity of integrating such circular principles and concepts into industrial, academic, and policymaking frameworks. This complexity underscores the need for a holistic approach that encompasses technical, economic, and social dimensions, as highlighted throughout the study.

Circular Material Typologies

According to the analysis, the study reveals a lack of a unified CM definition. This fragmentation arises from varying disciplinary perspectives, each emphasizing different priorities—e.g., technical feasibility, market adaptability, or ecological compatibility. The various definitions can be distinguished depending on the focus of the related debate. The CM concept mainly focuses on the maintenance of material values from a long-term perspective. *Secondary Materials* (SM) concern economically valuable ingoing and outgoing materials compatible with recovering processes with functional substitution capability to replace virgin materials—providing equal or higher performances—with a great opportunity to influence the supply advancement. The *Recovered Materials* (RM) are intended as recyclates, previously waste, which turn out to have an economic value according to their recycling and/or reuse degree. Similar to RM, the *Secondary Raw Resources* (*SRR*) highlight the original waste source that can be transformed into high-quality, valuable SM through efficient recovery processes. While *primary* and *secondary detritus* characterize the size of the waste material, the *end-of-life product* concept is a less diffuse term referring to SRR that hardly allows closing the loop by recovery due to complex compositions.

In order to avoid the subordinate sense and the value-loss connotation of the "secondary" adjective, CM can be assumed as an umbrella (and prompted as preferred) term to define both the CM and SM categories. Overall, CM are intentionally designed. A CM might cover a variety of material derived from waste and secondary recovered resources highly valued for industries alongside new alternatives, e.g., carbon-negative matter with the newest sequestering carbon property. The ultimate aim of the design of such materials is to replace or substitute primary resources by maintaining the highest possible value and performative functions through open- or closed-loop systems, thus reducing reliance on virgin extraction. The substitution can be achieved by an equivalent performance compared to the replacing material, according to many variables in terms of usage, technical and functional requirements, time, etc. (Vadenbo et al. 2016). While developing CM, particular attention must be focused on designing the intrinsic property of materials in order to be resorbable, recyclable, or constitute value for other systems as a new input. The intertwining of both inherent and relational properties of CM reflects the circular capability of the material (Geldermans 2016). The absence of a shared understanding among expert academics hinders the development of standardized practices in CM experimentation (Fricke et al. 2024; Aliotta et al. 2024; Florez et al. 2024; Wijesekara et al. 2024; Aliotta et al. 2024). By establishing a common language and shared goals across disciplines, research priorities can align with practical applications.

Circular Material Flows

According to the taxonomic analysis results, the concept of circularity is central to the debate around the four thematic areas of interest. All the disciplines engaged emphasize the importance of maintaining the highest value of secondary resources in a closed circular systems network. One of the results of the literature review is that the classification of CM typologies allows the exclusion of the following materials from this category:

- Primary resources (such as virgin raw materials) are those that have not been cycled through a recovery or reuse process.
- Waste materials that cannot be recycled or recovered due to their inherent composition or contamination or irreversible degradation, making them impossible to be turned into usable forms, as they lack the physical or chemical properties necessary for recovery.
- Materials, while disposing or recovering, can create significant environmental or health hazards.
- Transformation of RM into valuable resources requires more virgin input than recovered content, and their complex composition makes separating them into recoverable parts difficult.

Excluded materials highlight the need for CM to be compatible with existing recycling technologies and be carefully designed to meet market or product requirements to coherently preserve the material quality perception. Furthermore, these exclusion criteria expand the knowledge about the CM categories, allowing for guiding future development toward materials that meet the requirements to be scaled up into mature and applicable forms.

Moreover, while addressing the fragmentation of CM definitions, the study proposes to characterize the concept of circularity further linked to the material dimension among research domains employing a core set of standardized criteria or thresholds of substitutive terminology. These can be derived from the taxonomy analysis. For example, CM can be adopted where the design presence occurs, and/or the evolution from RM to SM terms' adoption can be done by setting up a qualitative or quantitative threshold value, such as recycled content, value retention potential, complexity composition, and so on. Such performative levels can also be settled through the use of already existing assessment criteria such as the Material Circularity Indicator (Ellen MacArthur Foundation and Granta 2015). In that sense, intersections among the four areas of interest highlighted significant cross-overlaps that could benefit from merging knowledge and enriching impacts. Recovery strategies in CM require a strategic integration of narrowing, slowing, and closing cycle approaches (Bocken et al. 2016; Jørgensen and Pedersen 2018; Cobo et al. 2018; Hahladakis and Iacovidou 2019; Campbell-Johnston et al. 2020). These strategies ensure that both products and materials remain in use for as long as possible, thereby minimizing the demand for new resources. Redesigning for long-term use should align with technological advancements and the simplification of synthetic or inorganic material compositions. This ensures that CM can be processed repeatedly while minimizing property degradation.

A more aware circular-oriented design should aim at supporting the transition from an anthropocentric dissipative model to a restorative and regenerative one, allowing for the integration of sustainable principles while redesigning new visions, processes, practices, and paradigms of sustainable futures (Tonkinwise 2014; Irwin 2015; Emidi 2024). Design for circularity emerges as a driver for managing material flows effectively (Jørgensen and Pedersen 2018). Such an approach enables the effective recirculation of materials and the avoidance of value degradation over time. However, this is neither enough nor diffusible at an industrial level.

Since the large-scale industrial implementation involves a cascade logic, losing both economic value and durability over time, systemic collaboration among businesses, policymakers, and academics is essential to optimize CM flows on a local or decentralized scale, developing more robust remanufacturing systems (Bocken et al. 2016; Campbell-Johnston et al. 2020; Rotondi et al. 2024).

Market Challenges

Many rebound effects led to the challenge of large-scale industrial adoption (De los Rios and Charnley 2017; Dumée 2022; Squatrito and Ferrara 2023; Florez et al. 2024). Among other things, these include:

- the economic and supply barriers to scaling recovery and reuse processes;
- the technical difficulty of designing materials compatible with both biological and technological cycles;
- the social and cultural implications of adopting circular practices.

Advances in digital technologies for supply chain transparency (Despeisse et al. 2017), as well as recycling process enhancements like the diffusion of chemical recycling infrastructure (Fricke et al. 2024), offer additional opportunities to optimize CM flows and quality. CM need to be designed with the ability to be integrated into closed or open loops, regenerating their value through compatible recovery processes. Moreover, the article stresses the importance of shifting the research focus, or at least integrating, into the material analysis from a solely technical characterization to a more holistic perspective, engaging broader implications of CM. This means to include the *material experience* (Karana et al. 2015b; Lerma et al. 2022) for the consumer benefit enhancement toward the waste perception cultural reshape (Bozzola et al. 2017; Kulczycka et al. 2024; Rotondi et al. 2024). The interdisciplinary approach highlighted by the study reveals the capability of each of them to highlight different aspects of the same concept. The complement to each point of view results in a complex, realistic framework to deal with when developing a new CM from scraps. This alignment can foster collaborative projects engaging with both a material-driven and an LCA approach to bridge knowledge gaps. Variances in terminologies may limit communication and knowledge transfer, so that a shared reference and perceptible framework could lead to the integration of fragmented understanding of CM. Additionally, embedding circular principles into education and professional training can nourish new practitioners capable of managing and adapting to the complexities of CM development.

As reported by many authors (Karana et al. 2015a, 2015b; Parisi et al. 2017), creative innovation may arise by enabling the material to act as a driver in a creative designing process, evoking ideas and discovering opportunities for its development and applications. At the same time, poor information about ongoing experimental CM solutions does not allow technical assessments or limit their contribution on a short life frame (Dervishaj and Gudmundsson 2024). The comparison and combination of diverging perspectives allows for the consideration of both technical feasibility and marketable acceptability of CM, enhancing their capability to be applied across sectors and be transdisciplinarily studied. Overall, as observed in recent trends, most publications emphasize waste valorization through experimentation (Fricke et al. 2024; Aliotta et al. 2024; Florez et al. 2024; Wijesekara et al. 2024; Aliotta et al. 2024) to identify the greatest potential of CM and explore their most suitable pool of applications.

Conclusion

The article critically analyzed the role of CM within the CE framework, synthetizing insights from an interdisciplinary review of literature and highlighting both opportunities and challenges posed by their adoption in advancing circular practices. According to the taxonomic analysis, the resulting categorization of term variables concerning CM significantly remarks on their heterogeneous and multifaceted inherent nature. CM are defined as intentionally designed materials that maintain compatibility with biological and technical cycles, ensuring their value can be preserved through repeated reuse and recovering processes. Such a definition integrates the other textual variables depicted, crossing and partially bridging interdisciplinary theoretical constructs. This umbrella definition underscores the critical role of CM in reducing dependency on finite resources while promoting material efficiency. The proposed taxonomy framework can serve as a critical reference for academics aiming to align empirical research with theoretical models, policymakers striving to design effective circular regulations, and industry professionals seeking actionable pathways toward sustainability. Moreover, the study proposes taxonomy both as a map of existing definitions and as a reference for standardized definitions among research domains. By adopting threshold values, such as intentional design presence, or by using existing criteria, the practical application of the taxonomy may be of use as a decision-making tool, fostering clarity in both research and practice.

Several challenges were identified in the integration of CM into CE systems. For example, technological limitations, such as the downgrading of material properties during recycling processes, remain a significant barrier (Lerma and Dal Palù 2019). Additionally, the complexity of designing materials that balance long-term durability with composition simplification highlights the trade-offs inherent in material innovation. Market-related challenges, including inconsistent regulatory frameworks and limited demand for SM, further complicate the adoption of such materials.

The findings underscore the importance of a holistic approach that considers technical, economic, and social dimensions by design. This approach aims to achieve the scalability and implementation of CM across diverse contexts, overcoming barriers of circularity and designing in symbiosis with the new material value stream (Pasold 2023).

The article positions design, and particularly the MD approach, as a driver for the transition to CE. Through its ability to integrate technical, economic, and social dimensions, MD enables the creation of solutions that are both scalable and aligned with sustainability goals, shaping CM properties to meet both functional and circular objectives. Further studies can try to deepen the spectrum of references adopted in both academic and applicative fields, identifying, for example, metrics to align the priorities of the different disciplines—avoiding falling into an over-simplification—or between industrial sectors to be more easily standardized and adapted in circular manufacturing processes available for industries. To enhance the impact of the study, essential work should be done to prioritize the development of a shared glossary classification system and viable related strategies, enabling clearer standardization across various research, industry, and regulatory domains.

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Noemi Emidi: investigation, methodology, validation, writing, review, and editing. Beatrice Lerma: methodology, supervision, and review. Dina Jacobsen: supervision, review, and validation. Anke Pasold: supervision, review, and validation. Claudia De Giorgi: review and validation.

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While the authors acknowledge the usage of AI, the authors maintain that they, Noemi Emidi, Beatrice Lerma, Dina Jacobsen, Anke Pasold, and Claudia De Giorgi, are the sole authors of this article and take full responsibility for the content therein, as outlined in COPE recommendations.

Informed Consent

The authors declare that informed consent was not required as there were no human participants involved.

Conflict of Interest

The authors declare that there is no conflict of interest.

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