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Keep circularity meaningful, inclusive and practical: A view into the plastics value chain

Ciprian Cimpan [a], Eleni Iacovidou [b], Lucia Rigamonti [c], Eggo U. Thoden van Velzen [d,*]

[a] SDU Life Cycle Engineering, University of Southern Denmark, Denmark
[b] Division of Environmental Sciences, College of Health, Medicine and Life Sciences, Brunel University London, United Kingdom
[c] Civil and Environmental Engineering Department, Politecnico Di Milano, Italy
[d] Wageningen Food & Biobased Research, Wageningen University & Research, Netherlands

A R T I C L E I N F O

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A B S T R A C T

New policies to promote the circular economy have created an urgent need for businesses and public authorities to quantify and monitor the level of circularity of materials, components and products. However, flows of materials, components and products through society are inherently complex, involving intricate value chains, many stakeholders, and interests. We argue that current actions may be overly focused on superficial effects, and losing sight of true circular economy goals. Using plastic packaging as an example, the present contribution deliberates the questions, "does measuring circularity address its goals?", "does it cover new technologies and regional specificities?", and "can its goals be addressed with simple assessment approaches?". In answering these questions, we argue that there is an impending risk of cementing policy and infrastructures that may not contribute to true sustainability. Furthermore, future technologies and developing regions are hardly included in the current circularity strategies. To further spark a discussion on the challenge of simplicity, we present a scorecard which can help incumbents to approximate the level of sustainable circularity of their products.

1. Introduction

The circularity of packaging materials, components and products is now a major trajectory taken by politicians and businesses to curb the negative environmental impacts caused by packaging life cycles including but not limited to greenhouse gas emissions, environmental pollution, and depletion of natural resources. As a result, packaging applications have received unprecedented attention over the past years. The European Commission is revising for the second time (in a short period) the packaging and packaging waste directive, with a focus on achieving increasing levels of packaging circularity (COM(2022) 677). Concurrently, national governments are initiating new laws on packaging waste (e.g., France: LOI n° 2020-105; Spanish Law 7/2022) and the business community is committing to ambitious targets to increase their circularity (Kahlert and Bening, 2022).

Assessing progress towards circularity implies that we have the tools for it and that the methodologies are fit-for-purpose and practical. In reality, this is not the case. Circularity is a broad concept, increasingly used to guide or benchmark the approaches used by businesses, industry, and policymakers to transition towards a direction that is compatible with the broader objective of sustainability. Defining circularity is still challenging and currently there is no widely accepted set of metrics that can capture both its efficiency and causal effects. It is safe to state however, that circularity is not necessarily synonymous with sustainability (Rigamonti and Mancini, 2021), and striving to achieve it will not guarantee sustainable outcomes (Blum et al., 2020).

This "Timely Advances in Waste Management" aims to rekindle and refocus research and discussion on circular economy (CE) goals, and related decision-making in policy and business. The paper briefly reviews some fundamental drawbacks around the operational application of CE strategies and analyses aspects defining packaging circularity and associated indicators, concluding with the presentation of a simple circularity scorecard for early product appraisal. Emphasis is placed on plastic packaging and polyethylene terephthalate (PET) is used as a case study to test the scorecard. The paper adopts a product-centric approach, although we use material, component and product systems,

Abbreviations: CE, Circular economy; EoL, End of Life; EU, European Union; PET, Poly(ethylene terephthalate); PtX, Power-to-X; rPET, Recycled poly(ethylene terephthalate).

* Corresponding author.
E-mail address: ulphard.thodenvanvelzen@wur.nl (E.U. Thoden van Velzen).

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and recycling processes in our argumentation.

2. Meaningful principles for measuring circularity

As pointed out by previous researchers, several drawbacks cast a shadow over the perception and implementation of CE by business, policy, and in research. While we touch on a few here, one could look at the recent work of Corvellec et al. (2022) for a comprehensive review.

A recurrent critique in CE implementation points to the neglect of basic knowledge, such as thermodynamics. Accordingly, a CE that is free of waste with perfectly closed loops, where materials are recycled indefinitely, is simply impossible to achieve (Reuter et al., 2019). Every material cycle or loop creates dissipation and entropy, which then requires new materials and energy to replenish (Cullen, 2017; Skene, 2018). In relation to material quality and functionality, two approaches are distinguished: open-loop recycling and closed-loop reuse and recycling. In open-loop recycling (or cascading, or downcycling) systems, a loss of quality of the material is accepted and the recycled material is used, typically, in lower quality (less demanding) applications. Within closed-loop systems, the quality of the materials is maintained and thus can be used in the same application. However, there may be losses or certain material attributes that need to be maintained and therefore, these may be replenished and compensated with virgin materials. Thus, there is no such thing as circular materials, components, and products; there are only different degrees of circularity or resource efficiency, dependent on inherent, designed and created attributes and external variables (Iacovidou et al., 2019).

As argued by Geyer et al. (2016) in achieving circularity *"it matters not only how much material is recycled, but also what it is recycled into and therefore can displace"* (p. 1011). This is especially relevant for open-loop systems, whereby materials of the same or diminished quality are used in making components and products other than the original product (e.g., bottle-to-fleece vs. bottle-to-bottle). Using resources in ways that are different to their original use can result in different or reduced resource savings and may lead to a net expansion of overall material consumption, mandated by longevity, frequency of production, and the number of life cycles the material can withstand (Geyer et al., 2016). A lack of insight into these aspects could lead to an increased likelihood of the so-called rebound effects (Zink and Geyer, 2017), which can negate the potential environmental savings associated with avoided primary production - a main impetus for circularity (Kirchherr et al., 2017). This points to the risk of unintendingly cementing frameworks of "circularity for circularity's sake" (Harris et al., 2021). Thus, we argue for increased tracing requirements (of sources) for secondary materials, especially in conjunction with current and upcoming recycled content rates requirements.

The markets for primary and secondary plastics lack integration and this sets the plastic value chain apart from other packaging material value chains, i.e., metals, glass, and paper/wood. In part, this is because plastics are a small (but growing) part of the highly complex and large-scale petrochemical-based products produced by the petrochemical industry (Bauer et al., 2022). The industry is characterized by processes with high efficiency but little flexibility towards secondary inputs. Complexity is further compounded by the great variety of plastic conversion (product manufacture) processes, which insofar have been little affected by policy pressure, which is mostly targeted at the end-of-life and secondary sectors. The lack of integration or even competition between primary and secondary sectors is also reflected in the instability of trade markets for secondary plastic materials. To this end, the current policies that put emphasis on recycled content and reuse, are likely to encourage integration, empower the secondary sector, and enforce the design of materials, components, and products that are reusable or substitute primary/virgin materials. Amidst these changes, one has to also factor in the misalignment in current and future policies, such as those that promote alternative materials (e.g., biobased, biodegradable alternatives), sustainable and safe by design products and quality standards of secondary materials (Blum et al., 2020; Leslie et al., 2016). Research is slowly unpacking the limitations around this issue.

To monitor and measure the implementation of CE, a wide variety of CE metrics have been developed. None of them, however, are measuring CE well or sufficiently enough, leading to some form of burden shifting between material consumption and environmental, economic, technical, or social aspects (Corona et al., 2019; Iacovidou et al., 2017). Additionally, current CE metrics underrepresent the complexities of slowing, closing, and narrowing material loops (Geissdoerfer et al., 2017). With plastics, an excessive focus is currently put on closing material loops, with or without a consideration of how many closed loops a material undergoes, while there is little measure of material, component, and product longevity (so-called slow material loops, where materials, components and products are retained in the system for longer before they enter further loops). We find a general lack of research on the lifecycle that certain materials, components, and products can be subjected to before degrading to a degree where they are no longer useful. The question of how many use cycles certain materials can have, has been widely researched for metals (Pauliuk et al., 2017). For example, a long residence time is an indication of the cumulated service provided by that material (Pauliuk, 2018). Indicators that cumulate the number of times and the length of time a material remains in use are important, such as those proposed for example by Figge et al. (2018). Cumulated service indicators have yet to be applied to plastics.

To conclude this section, it is important to highlight that there is an inherent complexity in measuring the value and effects of circular products or approaches, from an industrial, business and policy perspective. The development and measuring of circularity, and the monitoring of circularity processes, require indicators that are fit-for-purpose, easy to understand and use over time (scalable) (Iacovidou et al., 2019). These indicators must be complemented by comprehensive sustainability assessments (covering the three pillars of environment, economy, and society). Further, sustainability assessment should include rebound effects and trade-offs. The main imperative is to promote changes that deliver fewer trade-offs and create an intense and sustainable spiralling effect, instead of focusing on the unrealistic perfect circle.

3. Futureproofing by being inclusive

There are several topics one must address under inclusiveness: (1) the expanding portfolio of technical approaches to deliver circularity, e.g., thermochemical recycling; (2) the highly contextual nature of the CE and significance of trade, e.g., its dependency on spatial (geographical) and temporal (time) conditions; and (3) the human factor in a CE.

Closing plastic material loops and extending plastic product lifetimes, will likely occur only by combining different approaches and technologies, such as reuse, mechanical and thermochemical recycling, and carbon dioxide capture and use. Increasingly more "complex" approaches to circularity are expected. For example, in a possible future, incineration of plastic waste combined with carbon capture, and followed by power-to-x (PtX) plastics, may be the backbone of a circular system (at the level of carbon). Owing to the high complexity (polymer mixing, adhesives, and coatings), great variety of polymer additives, and degradation during use (Hahladakis and Iacovidou, 2019), some plastic applications (including certain packaging) are likely never going to be designed or made suitable to current conventional plastics (mechanical) recycling (Brouwer et al., 2020; Ragaert et al., 2017). Therefore, technology portfolio expansion is unavoidable and circularity metrics or indicators will have to be applicable also to these processes. With thermochemical recycling and PtX, the source of the plastic waste, and indeed the difference between closed- and open-loops, becomes irrelevant. To be inclusive, a parsimonious approach could then be to measure circularity by tracking the recycling of carbon (the main component of plastics).

However, new applications should be viewed through a critical lens.

Closing the carbon loop, e.g., thermochemical recycling and PtX, does not create a Perpetuum Mobile, as only a part of the carbon can become new plastics, and especially PtX requires ample amounts of renewable energy to achieve sustainability (Schirmeister and Mülhaupt, 2022). PtX should, however, be seen from a broader perspective of systems integration (energy and materials) that goes beyond plastics.

Another critique of the CE is its lack of representation of realities in developing countries and the Global South specifically (Cook et al., 2022). These regions are expected to account for most of the resource consumption and waste generation in the future. Products today flow through multi-regional supply chains and companies sell their products to global markets. The condition (or goal) of circularity is dependent on surrounding (contextual) framework conditions (e.g., political landscape, national legislation, local markets, and available infrastructure) (Iacovidou et al., 2021). Different circular economy strategies will likely be feasible (implementation-wise) in various regions and will likely result in very different effects, which points to the fact that there are no-one-size-fits-all solutions to circularity.

The topic of waste trade, for plastics, is highly contentious. In Europe, export possibilities have stood for a long time as an outlet for uneconomic and difficult to recycle plastics. As a reaction to increasing evidence of pollution (see e.g., Bishop et al. (2020)), today the possibility of a complete ban on export is increasingly put on the table. Although seldom addressed, imports of recycled materials, especially plastics, create a similar set of problems. On the one hand, they shift the burden of production outside Europe, while on the other hand they may endanger consumers health and safety due to potential risks of legacy chemicals migrating into food due to lower standard recycling processes. Nevertheless, while these concerns are valid, they should be addressed by better control mechanisms and more support for developing regions, considering that significant amounts of what we consume come from- and what we export/sell will be consumed and discarded outside Europe (Gerassimidou et al., 2022).

At the intersection of technology and regional context, there is a need to also recognise the limits of human behaviour, both in participation in sustainable production and consumption practices and in end of life (EoL) resources management, including recycling. Without extending into the much-varied conditions around the world, in Europe alone, separate collection systems face enormous challenges due to socio-economic differences, local implementation approaches, as well as cultural and awareness differences (Cimpan et al., 2015). While rural areas face the technical challenges of collection coverage, urban areas, where citizens are more disconnected from interaction with collection services (i.e., by common services), are universally problematic in terms of citizen participation (Knickmeyer, 2020). Sorting facilities for post-consumer mixed waste can and are contributing to recovering additional packaging waste in many countries. Nevertheless, the EU CE policy has gained an increasingly "moral" dimension, whereby certain waste management approaches become (politically) disqualified from the market (Gregson et al., 2015). This creates the impetus for moving away from disposal (when targeting landfill and incineration) but ignores the limits of human behaviour with separate collection. Post-consumer sorting solutions are associated with a loss in environmental awareness; however, consumer psychology research shows that participation in a separate collection scheme can act as a "moral license" to consume (more) (van Doorn and Kurz, 2021). While maintaining our precept of inclusivity in management approaches, we want to strongly encourage more research anchoring the largely techno-centric circular economy to socioeconomics and business and consumer psychology.

Finally, if policymakers and businesses are to create meaningful change by adopting circular economy principles, there is an imperative need to tackle misalignments and develop a means to measuring impacts across the entire value chain to enable selective interventions that focus on improving productivity and resource efficiency in the system as a whole. As evidenced by the recent health crisis (Covid-19 pandemic) and conflicts (Russia-Ukraine) the reliance on primary resources and off-shore production of components/products bolster the risk of down-prioritising circularity. Volatility in commodity prices could soon become the new norm and this will distort investments, halt and reverse plans to reform policies and create a stagnant economy that will resort to operating based on the well-established linear model (Ebner and Iacovidou, 2021). We need to prevent losing sight of what is beneficial in the long-term.

4. Simplicity over complexity: An impossible task?

A circularity indicator can be defined here as a quantitative or qualitative factor or variable that provides a simple and reliable means to assess and monitor the performance of systems in a CE perspective (OECD, 2014). Saidani et al. presented an overview of 55 sets of circularity indicators (Saidani et al., 2019). The indicators described vary based on their objectives, the assessment level (macro, meso, micro), the intended user group (civil servants, engineers, designers, scientists) and the level of detail in the data that needs to be entered. It was recognised early on that the collection and recycling rates are insufficient as circularity indicators as they fail to consider the quality of the secondary materials, and in which applications they are used (Haupt et al., 2016). Likewise, recycled content disregards the origin of secondary materials. More complex indicators such as the material circularity indicator of the Ellen MacArthur Foundation examines all material flows but do not take the quality of the secondary materials into consideration (Bracquené et al., 2022). To account for the quality of the secondary materials, Huysman developed the circular economy performance indicator (Huysman et al., 2017) and the recycling benefit rate (Huysman et al., 2019), which rely on exceedingly complex LCA-based data in combination with subjective assessments. For many materials, components and products circularity is just one of the many aspects that are considered in sustainability assessments. Frojan et al. recently presented a review of the environmental assessment methods to evaluate packaging sustainability and suggested a new scoring methodology in which aspects of circularity are integrated (Frojan et al., 2023).

It is likely that complex combinations of indicators may be the only suitable approach to qualify a product or process as circular and sustainable. However, if wide adoption of circular approaches is the goal, complex indicators may be outside the reach (e.g., costs with staff or consultancy services) of most of the business community. More widely, it is recognized that the means of assessing product circularity at early design phases is an area that lacks clear or suitable approaches (Saidani et al., 2017).

As a simple approach to tackle complexities regarding closed-/open-loop systems, we propose a circularity scorecard which captures aspects that are likely to indicate the environmental sustainability of a product (through its life cycle). It is a "common sense" approach and has parallels to the waste hierarchy, which could work in a similar way, i.e., a simple priority order that most often holds true. Its application, by businesses, for example, could screen for viable new product/packaging designs.

5. Circularity scorecard for prioritising environmental sustainability aspects

Taking the theoretical case of a new product or packaging (using secondary, primary or a mixture of materials) the scorecard addresses seven overarching questions (Fig. 1): three at the production stage, one at the use stage, and three at the EoL stage. The answers given should consider the prevailing contextual conditions at the location and time of evaluation. A single score can then be derived by summing the individual scores (consisting of + and -) assigned to each of the questions. This single score provides an indication of the level of circularity: the higher the score the more circular the product is likely to be, and the higher the potential for returning environmental benefits in terms of sustainability. In a future use, both the scorecard'scores and the summed

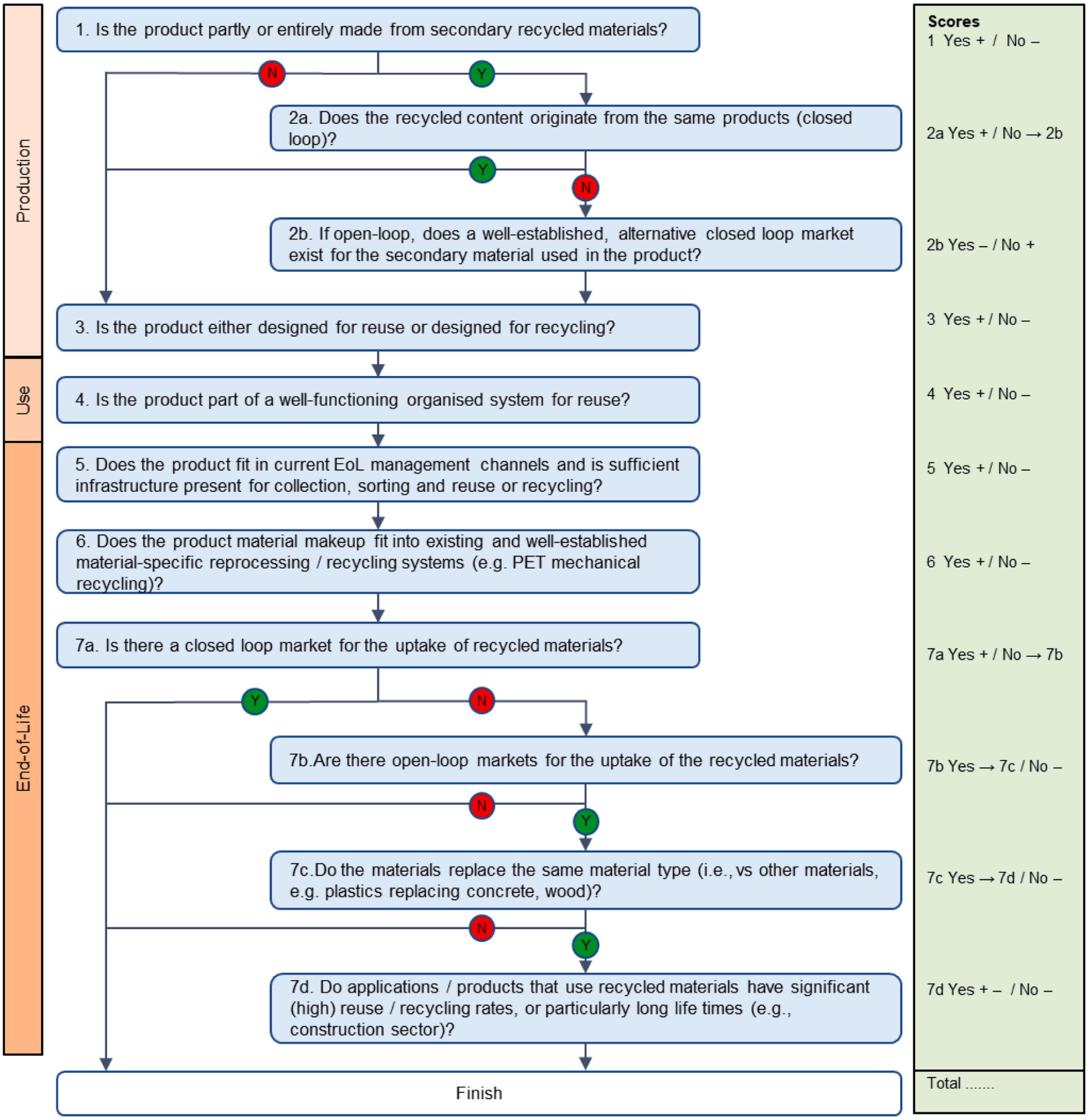

Fig. 1. Circularity scorecard, the Y in the green circle represents a “yes” answer to the question and the N in the red circle represents a “no” answer. For most questions + or – scores are given, which are listed in the right panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

total, should be simultaneously used, to facilitate a deeper interpretation of the circularity potential.

At the production stage: The first two questions are concerned with the origin or materials used in production, including the sourcing of secondary (recycled) content, which can be either from closed-loop recycling (of products with the same function as the one evaluated) or open-loop recycling. With open loop the question breaks down to sub-questions, to further explore if well-established closed loop markets already exist for the sourced materials. If the answer is ‘no’, the use of these materials in current products may create new cycling and market demand with beneficial effects, while a positive (‘yes’) answer may indicate that materials are taken from another closed-loop, and potentially downcycled in this application. In the case of plastics, the form of recycling referred to here, is the currently prevailing mechanical recycling. The scorecard could be expanded to include secondary plastics from thermochemical, PtX (as they become available) and bio-based feedstock. For the latter key questions that could be added include “Does the product contain biobased material content? And if so, is the biobased feedstock used for production of food?”. The next question addresses design for EoL, specifically if this is considered by compliance or following a specific design guideline or standards (e.g., www//recyclass.eu).

At the use stage: The main question at this stage aims to explore if the product is part of well-functioning organized system for reuse. This question is most relevant for packaging, although could become relevant for other products in the future (e.g., textiles).

At the EoL stage: this stage aims to consider contextual settings (e.g., location), with the first question establishes the products’ compatibility with existing EoL management channels and infrastructure/technologies in the markets the product is sold and eventually discarded. This means potential capture by separate collection and efficient sorting in materials recovery facilities (MRFs). It includes existing depositreturn (including those for reusable packages) systems. The next question narrows in on final reprocessing/recycling, rating the products' compatibility with existing, well-established material-specific processes (e.g., PE mechanical recycling). The final question addresses the existence of a closed-loop market for uptake of the recycled materials (recovered from the product). This means the return of materials back to the production of the same product. With a negative answer, the question breaks down into sequential sub-questions that explore further if the recovered materials replace the same or other material types (e.g., plastics replacing concrete, and wood). The latter would indicate a broken cycle and likely little environmental benefits. Finally, open-loop utilisation where the same material is substituted, could still induce benefits, especially if the new application/products have significant (high) recycling rates, or particularly long lifetimes (e.g., construction sector). This is awarded a neutral (+-) rating. Fig. 1 illustrates the circularity scorecard.

6. Case study for PET packaging

In the following section, we employ the proposed circularity scorecard, using PET packaging as a case study. The contextual settings refer to Europe in 2022.

Global production of PET is already over 80 Mt, with the main application sector being fibres (e.g., for textiles) at around 64%, and the remaining 36% used in packaging applications. Similarly, globally 55–60% of recycled PET (rPET) is used in fibres (Joo and Oh, 2019). Almost all recycled polyester in the textile industry is based on bottle PET and not originating in recycled textiles (Lorenz, 2021; Manshoven et al., 2021). Polyester (PET) in textiles is very difficult to recycle, as it is often mixed with other materials, dyes, and additives. Less than 1% of textile waste is currently recycled (fibre to fibre) into new clothing in Europe and arond 10% is recycled open-loop in cleaning rags, thermal insulation, etc. (McKinsey & Company, 2022). These are conditions taken in the test shown in Table 1.

PET beverage bottles are collected and sorted for recycling at 61% in Europe (Eunomia, 2020). The quality of the produced rPET depends on the design of the PET bottles and the collection method. Overall, 32% of the produced rPET (from bottles and trays) was used to blow new bottles, 33% was used to make a new sheet for trays, 24% for fibres (textiles), 8% for strapping and 3% for miscellaneous applications (Grant and Lahme, 2022). Open-loop recycling suffers from a lack of transparency. With the rPET market in Europe being under pressure, prioritising policies that can support the circularity of this high-quality material in a way that supports sustainability benefits is essential. The consideration of regulatory requirements on new plastic packaging (such as the UK plastic packaging tax) and pledges from the textile industry for used recycled feedstocks create antagonistic pathways in the current value chain, that should be further addressed with policy. The gap between the potential supply and demand of rPET represented by the quantification of industry pledges could soon be as high as 1 Mt (Kahlert and Bening, 2022). As a likely indication of market constraints, a doubling of the price of rPET was already observed during 2021–2022.

Table 1 shows that the level of circularity of a material, component or product relates both to its design and the presence of collection, sorting and reuse/recycling infrastructure. This is attributed to the spatial and temporal dimension of circularity, and it implies that before the right infrastructure is in place, a material, component, or product may be classified as non-reusable/recyclable and therefore linear (non-circular). Furthermore, various entrepreneurial activities such as the production and use of biobased PET or the inauguration of thermochemical recycling facilities do not engender circularity by themselves when surrounding infrastructures and markets are missing.

Table 1
Test of the scorecard with products made partly with rPET from beverage bottles.

Nr.	Scorecard question	PET single-use bottle	PET multi-use bottle	PET tray	T-Shirt (50% polyester, 50% cotton)
1	Product partly or entirely made from secondary recycled materials?	+	+	+	+
2a	Does the recycled content originate from the same products?	+	+	na	na
2b	Does a well-established closed-loop market exist for the secondary material?	na	na	–	–
3	Is the product either designed for reuse or designed for recycling?	+	+	–(*)	–
4	Is the product part of a well-functioning organized system for reuse?	–	+	–	–
5	Does the product fit in current EoL management channels and is there sufficient infrastructure present?	+	+	+	–
6	Does the product material makeup fit into existing and well-established material-specific reprocessing/recycling systems?	+	+	– (*)	–
7a	Is there a closed-loop market for the uptake of recycled materials?	+	+	na (*)	na
7b	Are there open-loop markets for uptake of the recycled materials?	na	na	na	na
7c	Do the materials replace the same material type (i.e., vs. other materials, e.g., plastics replacing concrete, wood)?	na	na	na	-
7d	Do applications/products that use recycled materials have significant (high) reuse/recycling rates, or particularly long lifetimes?	na	na	+– (**)	na
Total		6+/1–	7+	2+/4–	1+/6–

na: not applicable; (*) this score will turn positively in the future when new recycling processes have been implemented widely throughout Europe and the trays have been redesigned accordingly; (**) this refers to the case that PET trays made from recycled bottles are used in automotive and construction applications with a long life-time.

7. Conclusions

The circularity of materials, components or products is a deceptively parsimonious term. Governments, industries and businesses strive towards a higher degree of circularity for consumer goods and often use collection rates, recycling rates, recycled content, biobased content and alternatives, substitutability, etc. as indicators to veer towards circularity. When the circularity is measured with such indicators, they can hinder our ability to capture system realities and effects of systemic transformation. This, in turn, engenders important externalities and rebound effects that are often overlooked in decision-making processes, hence potentially creating more problems than solving ones. In an attempt to refocus discussion among scientists on how circularity should be measured, we presented a scorecard that encompasses relevant aspects of environmental sustainability and used the PET beverage bottle as a case study. Is this scorecard sufficient to capture all aspects of circularity? No. Nevertheless, it is a good starting point that we can further build upon and use as guidance in promoting circularity in the plastics value chain.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

References

Bauer, F., Nielsen, T.D., Nilsson, L.J., Palm, E., Ericsson, K., Fråne, A., Cullen, J., 2022. Plastics and climate change breaking carbon lock-ins through three mitigation pathways. One Earth 5, 361–376. https://doi.org/10.1016/J.ONEEAR.2022.03.007.

Bishop, G., Styles, D., Lens, P.N.L., 2020. Recycling of European plastic is a pathway for plastic debris in the ocean. Environ. Int. 142, 105893 https://doi.org/10.1016/j.envint.2020.105893.

Blum, N.U., Haupt, M., Bening, C.R., 2020. Why "Circular" doesn't always mean "Sustainable". Resour. Conserv. Recycl. 162, 105042 https://doi.org/10.1016/j.resconrec.2020.105042.

Bracquené, E., Dewulf, W., Duflou, J.R., 2022. Measuring the performance of more circular complex product supply chains. Resour. Conserv. Recycl. 154, 104608 https://doi.org/10.1016/j.resconrec.2019.104608.

Brouwer, M.T., Thoden van Velzen, E.U., Ragaert, K., ten Klooster, R., 2020. Technical limits in circularity for plastic packages. Sustainability 12, 10021. https://doi.org/10.3390/su122310021.

Cimpan, C., Maul, A., Jansen, M., Pretz, T., Wenzel, H., 2015. Central sorting and recovery of MSW recyclable materials: a review of technological state-of-the-art, cases, practice and implications for materials recycling. J. Environ. Manage. 156, 181–199. https://doi.org/10.1016/j.jenvman.2015.03.025.

COM(2022) 677 PARLIAMENT AND OF THE COUNCIL on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0677.

Cook, E., Velis, C.A., Cottom, J.W., 2022. Scaling up resource recovery in the emergent circular economy to prevent plastic pollution: assessment of risks to health and safety in the Global South. Waste Manage. Res. 40 (12), 1680–1707. https://doi.org/10.1177/0734242X221105415.

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., Worrell, E., 2019. Towards sustainable development through the circular economy—a review and critical assessment on current circularity metrics. Resour. Conserv. Recycl. 151, 104498 https://doi.org/10.1016/J.RESCONREC.2019.104498.

Corvellec, H., Stowell, A.F., Johansson, N., 2022. Critiques of the circular economy. J. Ind. Ecol. 26, 421–432. https://doi.org/10.1111/JIEC.13187.

Cullen, J.M., 2017. Circular economy: theoretical benchmark or perpetual motion machine? J. Ind. Ecol. 21, 483–486. https://doi.org/10.1111/jiec.12599.

Ebner, N., Iacovidou, E., 2021. The challenges of Covid-19 pandemic on improving plastic waste recycling rates. Sustain. Prod. Consum. 28, 726–735. https://doi.org/10.1016/j.spc.2021.07.001.

Eunomia, 2020. PET Market in Europe - State of Play: production, collection and recycling data. Brussels. URL: https://www.eunomia.co.uk/reports-tools/pet-market-in-europe-state-of-play/.

Figge, F., Thorpe, A.S., Givry, P., Canning, L., Franklin-Johnson, E., 2018. Longevity and circularity as indicators of eco-efficient resource use in the circular economy. Ecol. Econ. 150, 297–306. https://doi.org/10.1016/j.ecolecon.2018.04.030.

Frojan, J., Bisquert, P., Buche, P., Gontard, N., Boone, L., Nhu Thuy, T., Vermeulen, A., Ragaert, P., Dewulf, J., Guillard, V., 2023. Scoring methodology for comparing the environmental performance of food packaging. Packag. Technol. Sci. https://doi.org/10.1002/pts.2720.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The circular economy – a new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048.

Gerassimidou, S., Lanska, P., Hahladakis, J.N., Lovat, E., Vanzetto, S., Geueke, B., Groh, K.J., Muncke, J., Maffini, M., Martin, O.V., Iacovidou, E., 2022. Unpacking the complexity of the PET drink bottles value chain: a chemicals perspective. J. Hazardous Mater., 128410 https://doi.org/10.1016/j.jhazmat.2022.128410.

Geyer, R., Kuczenski, B., Zink, T., Henderson, A., 2016. Common misconceptions about recycling. J. Ind. Ecol. 20 (5), 1010–1017. https://doi.org/10.1111/jiec.12355.

Grant, A., Lahme, V., 2022. PET market in Europe, state of play 2022. Eunomia, Bristol (UK), 31 Jan 2022. URL: https://www.eunomia.co.uk/reports-tools/pet-market-in-europe-state-of-play-2022/.

Gregson, N., Crang, M., Fuller, S., Holmes, H., 2015. Interrogating the circular economy: the moral economy of resource recovery in the EU. Econ. Soc. 44, 218–243. https://doi.org/10.1080/03085147.2015.1013353.

Hahladakis, J.N., Iacovidou, E., 2019. An overview of the challenges and trade-offs in closing the loop of post-consumer plastic waste (PCPW): focus on recycling. J. Hazard. Mater. 380, 120887 https://doi.org/10.1016/j.jhazmat.2019.120887.

Harris, S., Martin, M., Diener, D., 2021. Circularity for circularity's sake? scoping review of assessment methods for environmental performance in the circular economy. Sustain. Prod. Consum. 26, 172–186. https://doi.org/10.1016/J.SPC.2020.09.018.

Haupt, M., Vadenbo, C., Hellweg, S., 2016. Do we have the right performance indicators for the circular economy? J. Ind. Ecol. 21 (3), 615–627. https://doi.org/10.1111/jiec.12506.

Huysman, S., De Schaepmeester, J., Hubo, S., Ragaert, K., Dewulf, J., De Meester, S., 2017. Performance indicators for a circular economy: a case study on post-industrial plastic waste. Resour. Conserv. Recycl. 120, 46–54. https://doi.org/10.1016/j.resconrec.2017.01.013.

Huysman, S., Hubo, S., Ragaert, K., Dewulf, J., 2019. Advancing circular economy benefit indicators and application on open-loop recycling of mixed and contaminated plastic waste fractions. J. Cle. Prod. 211, 1–13. https://doi.org/10.1016/j.jclepro.2018.11.110.

Iacovidou, E., Velis, C.A., Purnell, P., Zwirner, O., Brown, A., Hahladakis, J., Millward-Hopkins, J., Williams, P.T., 2017. Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: a critical review. J. Clean. Prod. 166, 910–938. https://doi.org/10.1016/J.JCLEPRO.2017.07.100.

Iacovidou, E., Velenturf, A.P.M., Purnell, P., 2019. Quality of resources: a typology for supporting transitions towards resource efficiency using the single-use plastic bottle as an example. Sci. Total Environ. 647, 441–448. https://doi.org/10.1016/J.SCITOTENV.2018.07.344.

Iacovidou, E., Hahladakis, J.N., Purnell, P., 2021. A systems thinking approach to understanding the challenges of achieving the circular economy. Environ. Sci. Pollut. Res. 28, 24785–24806. https://doi.org/10.1007/s11356-020-11725-9.

Joo, E., Oh, J.-E., 2019. Challenges Facing Recycled Polyester [WWW Document]. Text. World - Featur. URL: https://www.textileworld.com/textile-world/features/2019/07/challenges-facing-recycled-polyester/ (accessed 9.27.22).

Kahlert, S., Bening, C.R., 2022. Why pledges alone will not get plastics recycled: comparing recyclate production and anticipated demand. Resour. Conserv. Recycl. 181, 106279 https://doi.org/10.1016/j.resconrec.2022.106279.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/J.RESCONREC.2017.09.005.

Knickmeyer, D., 2020. Social factors influencing household waste separation: a literature review on good practices to improve the recycling performance of urban areas. J. Clean. Prod. 245, 118605 https://doi.org/10.1016/j.jclepro.2019.118605.

Leslie, H.A., Leonards, P.E.G., Brandsma, S.H., de Boer, J., Jonkers, N., 2016. Propelling plastics into the circular economy — weeding out the toxics first. Environ. Int. 94, 230–234. https://doi.org/10.1016/j.envint.2016.05.012.

LOI n° 2020-105 du 10 février 2020 relative à la lutte contre le gaspillage et à l'économie circulaire (1). https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000041553759/.

Lorenz, P., 2021. Recycled Polyester and the Plastic Bottle Dilemma [WWW Document]. Circ, Lab.

McKinsey & Company, 2022. Scaling textile recycling in Europe: Turning waste into value. URL: https://www.mckinsey.com/industries/retail/our-insights/scaling-textile-recycling-in-europe-turning-waste-into-value#/.

Manshoven, S., Smeets, A., Arnold, M., Mortensen, L.F., 2021. Plastic in textiles : potentials for circularity and reduced environmental and climate impacts, European Topic Centre Waste and Materials in a Green Economy. URL: https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/plastic-in-textiles-potentials-for-circularity-and-reduced-environmental-and-climate-impacts/@@download/file/ETC_2.1.2.2._plastic%20in%20textiles_final_edited%20for%20website.pdf.

OECD, 2014. Measuring and Managing Results in Development Cooperation. URL: https://www.oecd.org/dac/peer-reviews/Measuring-and-managing-results.pdf.

Pauliuk, S., 2018. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resour. Conserv. Recycl. 129, 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019.

Pauliuk, S., Kondo, Y., Nakamura, S., Nakajima, K., 2017. Regional distribution and losses of end-of-life steel throughout multiple product life cycles—Insights from the global multiregional MaTrace model. Resour. Conserv. Recycl. 116, 84–93. https://doi.org/10.1016/j.resconrec.2016.09.029.

Ragaert, K., Delva, L., Van Geem, K., 2017. Mechanical and chemical recycling of solid plastic waste. Waste Manag. 69, 24–58. https://doi.org/10.1016/j.wasman.2017.07.044.

Reuter, M.A., van Schaik, A., Gutzmer, J., Bartie, N., Abadías-Llamas, A., 2019. Challenges of the circular economy: a material, metallurgical, and product design perspective. Annu. Rev. Mater. Res. 49, 253–274. https://doi.org/10.1146/annurev-matsci-070218-010057.

Rigamonti, L., Mancini, E., 2021. Life cycle assessment and circularity indicators. Int. J. Life Cycle Assess. 26, 1937–1942. https://doi.org/10.1007/S11367-021-01966-2.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., 2017. How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. Recycling 2. https://doi.org/10.3390/recycling2010006.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. J. Cle. Prod. 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014.

Schirmeister, C.G., Mülhaupt, R., 2022. Closing the carbon loop in the circular plastics economy. Macromol. Rapid Commun. 43, 2200247. https://doi.org/10.1002/MARC.202200247.

Skene, K.R., 2018. Circles, spirals, pyramids and cubes: why the circular economy cannot work. Sust. Sci. 13, 479–492. https://doi.org/10.1007/s11625-017-0443-3.

Spanish Law 7/2022. Fiscal measures in Law 7/2022 of 8 April on waste and contaminated soils for a circular economy. https://www.boe.es/buscar/act.php?id=BOE-A-2022-5809.

van Doorn, J., Kurz, T., 2021. The warm glow of recycling can make us more wasteful. J. Environ. Psychol. 77, 101672 https://doi.org/10.1016/j.jenvp.2021.101672.

Zink, T., Geyer, R., 2017. Circular economy rebound. J. Ind. Ecol. 21, 593–602. https://doi.org/10.1111/jiec.12545.