Exploring the landscape of circularity indicators: A systematic review with focus on nano- and micro indicators for the assessment of biobased materials and products

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EXTENDED ABSTRACT

The transition towards a circular economy necessitates reliable metrics for evaluating the effectiveness of circularity measures (e.g., reuse, remanufacturing, or recycling) employed in products and technologies (Peña et al., 2021). Various metrics and indicators have been proposed to measure circularity; however, due to their consideration of different aspects in their assessment, these tend to give varied results (Corona et al., 2019; Vural Gursel et al., 2023). To assess circularity on a sound basis, it is necessary to identify and utilize circularity indicators fit for a given context. Therefore, this paper aims to systematically explore proposed circularity indicators by classifying them according to multiple criteria, with a focus on their suitability for assessing specific R-strategies (as defined by Reike et al., 2018) and their ability to account for the use of biobased materials. In a second step, a set of suitable indicators will be applied to a case study of a novel wood-hybrid battery compartment (Krassnitzer et al., 2025; Wagner et al., 2024) for battery electric vehicles (BEV).

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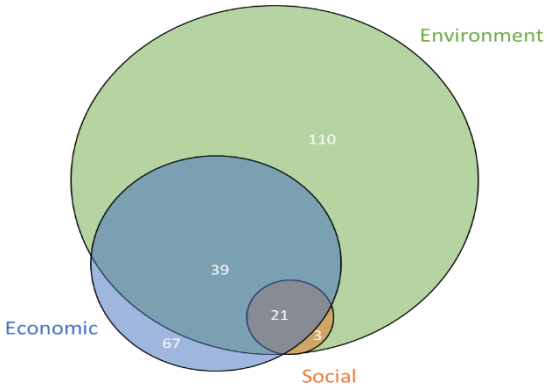

Figure 1: Dimensionality of the circularity indicators. The environmental dimension includes aspects such as the share of renewable materials, material waste, and emissions of a material or a product. Economic aspects include durability and utility, as well as value added. Social aspects may be the creation of jobs and social wellbeing.

This research is part of an ongoing effort to understand and enhance the circularity of renewable materials in contemporary manufacturing and product design. Therefore, a literature review has been conducted to identify relevant circularity metrics. Through the snowballing technique, circularity indicators have been extracted from previously conducted reviews on circularity metrics (Corona et al., 2019; Harris et al., 2021; Oliveira et al., 2021; Saidani et al., 2019; Vural Gursel et al., 2023). Additionally, a literature search within the date range of 2022-2025 with relevant search terms has been conducted. The identified indicators have been evaluated based on multiple criteria, such as their consideration of R-strategies, the consideration of biobased materials, the scale on which the indicator assesses circularity (material, product, companies or regional areas), the dimensionality (economic, environmental, and/or social) of the indicators, and more. The systematic literature search yielded 303 circularity indicators, of which 120 were deemed eligible for our study. These indicators are displayed in Figure 1 and are clustered by their dimensionality. As can be seen, 21 indicators were found that consider the environmental, economic, and social dimensions. Most of the indicators considered solely the environmental dimension (47), followed by indicators that account for both the economic and environmental dimensions (39), and a smaller fraction considered only economic aspects (7). From all investigated indicators, 69% assess circularity on a product level, 20% on the material

level, and the remaining 11% can assess on both scales. Figure 2 shows the number of indicators that account for a specific R-strategy.

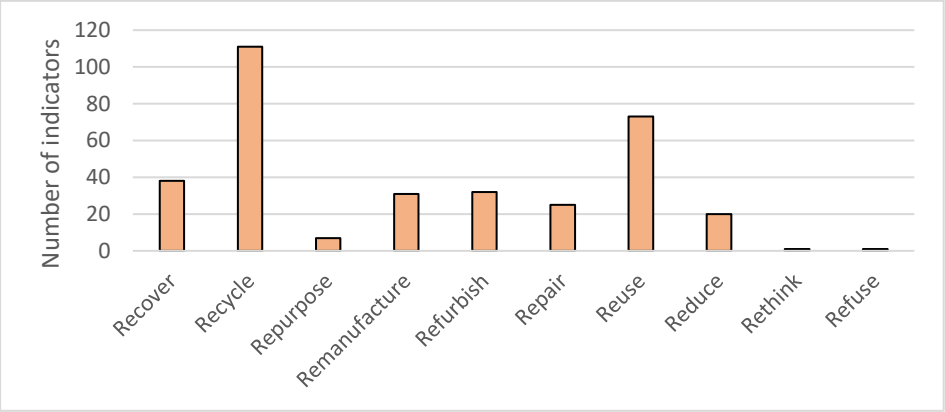

Figure 2: Indicators and their consideration of different R-Strategies

As can be seen, most indicators are able to account for the R-strategy Recycle (111), followed by Reuse (73) and Recover (38). Some indicators also account for different R-strategies such as Remanufacture (31), Repair (25), and Reduce (20). However, only two indicators account for the strategies Rethink and Refuse. Figure 3 displays the number of R-strategies that circularity indicators account for.

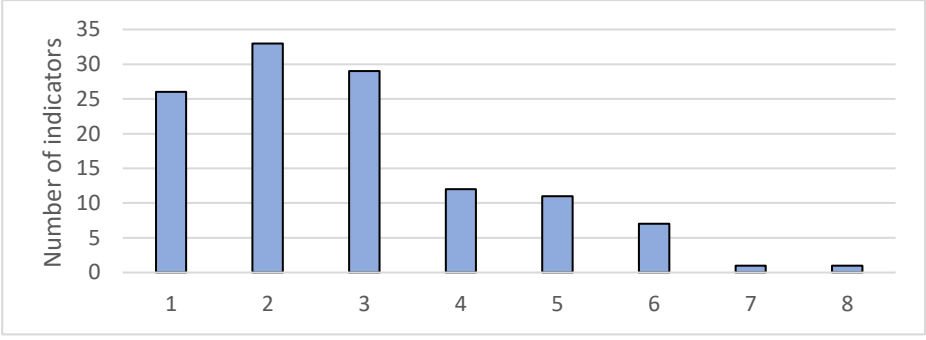

Figure 3: Number of R-Strategies covered by the indicators

It is apparent that most indicators account for a small number of R-Strategies; for example, 33 indicators account for 2 R-Strategies, and 29 indicators

account for 3 R-Strategies. A notable fact is that approximately 70% of the indicators consider only 3 R-strategies or fewer. However, two indicators stand out in this context: the 9R-Index (Muñoz et al., 2024) and the L&C indicator (Figge et al., 2018). These account for 8 and 7 R-strategies, respectively. The results indicate that assessing circularity is multifaceted, demonstrating the variability of aspects, scales, and scopes that need to be considered when evaluating circularity on various levels. Interestingly, many indicators do not even consider an environmental dimension and rely solely on economic and/or social aspects. This is somewhat unexpected, as circularity and the circular economy are closely tied to the concept of sustainability (Stahel, 2016). The focus on assessing established and well-known R-strategies, such as Recycle, and the lack of strategies like Refuse or Rethink, is also apparent in our results. The preliminary results of our study show that many indicators focus on the recyclability of materials and products. Since Recycling is considered the least preferred option from an environmental perspective, besides Recovery (Reike et al., 2018), the nature of those indicators may lead to a bias in attributing products a more circular character than they have. In other words, by not considering more preferable R-strategies than Recycling, the more effective R-strategies are not being credited enough in the face of a necessary transition towards a circular economy. Further work includes investigating the eligibility of the indicators to account for biobased materials and applying a set of indicators to the case study of a novel wood-hybrid battery compartment to benchmark them.

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REFERENCES

Corona, B., Shen, L., Reike, D., Rosales Carreón, J. y Worrell, E. (2019). Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resources, Conservation and Recycling, 151, 104498. https://doi.org/10.1016/j.resconrec.2019.104498

Figge, F., Thorpe, A. S., Givry, P., Canning, L. y Franklin-Johnson, E. (2018). Longevity and Circularity as Indicators of Eco-Efficient Resource Use in the Circular Economy. Ecological Economics, 150, 297–306. https://doi.org/10.1016/j.ecolecon.2018.04.030

Harris, S., Martin, M. y Diener, D. (2021). Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustainable Production and Consumption, 26, 172–186. https://doi.org/10.1016/j.spc.2020.09.018

Krassnitzer, P., Schlögl, G., Baumann, G., Feist, F., Oka, T., Haas, F., Wagner, M., Stern, T. y Mair-Bauernfeind, C. (2025). Wood you believe it? Electric vehicles and engineered wood from an environmental perspective. Discover Sustainability, 6(1). https://doi.org/10.1007/s43621-025-00957-9

Muñoz, S., Hosseini, M. R. y Crawford, R. H. (2024). Towards a holistic assessment of circular economy strategies: The 9R circularity index. Sustainable Production and Consumption, 47, 400–412. https://doi.org/10.1016/j.spc.2024.04.015

Oliveira, C. T. de, Dantas, T. E. T. y Soares, S. R. (2021). Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments. Sustainable Production and Consumption, 26, 455–468. https://doi.org/10.1016/j.spc.2020.11.024

Peña, C., Civit, B., Gallego-Schmid, A., Druckman, A., Pires, A. C., Weidema, B., Mieras, E., Wang, F., Fava, J., Canals, L. M. i., Cordella, M., Arbuckle, P., Valdivia, S., Fallaha, S. y Motta, W. (2021). Using life cycle assessment to achieve a circular economy. The International Journal of Life Cycle Assessment, 26(2), 215–220. https://doi.org/10.1007/s11367-020-01856-z

Reike, D., Vermeulen, W. J. y Witjes, S. (2018). The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. Resources, Conservation and Recycling, 135, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F. y Kendall, A. (2019). A taxonomy of circular economy indicators. Journal of Cleaner Production, 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014

Stahel, W. R. (2016). The circular economy. Nature, 531(7595), 435–438. https://doi.org/10.1038/531435a

Vural Gursel, I., Elbersen, B. y Meesters, K. P. (2023). Monitoring circular biobased economy – Systematic review of circularity indicators at the micro level. Resources, Conservation and Recycling, 197, 107104. https://doi.org/10.1016/j.resconrec.2023.107104

Wagner, M., Baumann, G., Lindbichler, L., Klanner, M. y Feist, F. (2024). Comparing the NVH Behaviour of an Innovative Steel-Wood Hybrid Battery Housing Design to an All Aluminium Design. Publicación en línea avanzada. https://doi.org/10.4271/2024-01-2949