sustainability

Article

Circularity Micro-Indicators for Plastic Packaging and Their Relation to Circular Economy Principles and Design Tools

Joana Matos [1], Carla I. Martins [1] and Ricardo Simoes [1,2,*]

[1] Institute for Polymers and Composites (IPC), University of Minho, 4800-058 Guimaraes, Portugal; id9458@alunos.uminho.pt (J.M.); cmartins@dep.uminho.pt (C.I.M.)
[2] Polytechnic Institute of Cavado and Ave (IPCA), 4750-810 Barcelos, Portugal
* Correspondence: rsimoes@ipca.pt

Abstract: Plastic packaging, in the form of films, brought several advantages to the commercialization of products given its lightness and durability. It provided better ergonomics, ease of transport, increased shelf life, and easy handling and use. Despite that, plastic packaging is facing enormous sustainability concerns associated with the traditional practice of linear economy, combined with commonplace irresponsible handling by citizens since it is almost exclusively designed for single-use and its end-of-life (EOL) management is not planned for. To mitigate that, the circularity of plastic packaging must be more clearly studied and evaluated through approaches such as micro-level circular economy (CE) indicators. This paper focuses on the selection of relevant CE micro-indicators specifically for the plastic packaging sector among the plethora of indicators available. Relations are also established between CE micro-indicators and CE guiding principles, as well as the most prevalent Design for X (DfX) approaches, providing new insights into how these different aspects of sustainability can be linked together. Results show three micro-level indicators as the most relevant for circularity calculation in packaging, namely those termed 'MCI', 'VRE', and 'CEIP', because their methodology and approach address most of the CE guiding principles and DfX approaches relevant for the packaging sector. Finally, guidelines and good practices to promote circularity adoption in the plastic packaging sector are highlighted. This work can guide companies aiming to adopt CE micro-indicators in their practical implementation, overcoming the significant knowledge barrier that currently exists.

Keywords: circular economy; circularity indicators; packaging; plastics; CE guiding principles; Design for X

Citation: Matos, J.; Martins, C.I.; Simoes, R. Circularity Micro-Indicators for Plastic Packaging and Their Relation to Circular Economy Principles and Design Tools. *Sustainability* **2024**, *16*, 2182. https://doi.org/10.3390/su16052182

Academic Editor: Antonio Boggia

Received: 8 January 2024
Revised: 9 February 2024
Accepted: 26 February 2024
Published: 6 March 2024

1. Introduction

Packaging should fulfill various purposes: containment, protection, preservation, identification, information exhibition and appeal to the market [1,2]. For plastic packaging, almost all non-biodegradable polymers are used, namely high- and low-density polyethylene (HDPE and LDPE, respectively), polypropylene (PP), and polyethylene terephthalate (PET) [3]. Of the plastic packaging applications, 73% correspond to plastic household packaging to preserve food, reduce damage and improve the lifecycle and appearance of products [4,5]. This type of packaging is currently still designed based on an open and linear resource consumer model, in which the lifecycle is less than one day, causing large amounts of plastic waste [5,6].

In 2022, the total European (EU27+3) plastics demand was 54 million tons, where packaging by far represented the largest end-use market (39%) [7]. In 2020, 17.9 million tons of post-consumer plastic packaging were collected, which corresponded to more than half (61%, approximately) of post-consumer waste collected that year. Packaging wastes collected were recycled (46%) or incinerated (37%), with energy recovery [3]. However, incineration is not the most environmentally friendly process due to the release of toxic gases during combustion [3,8]. The short lifetime of plastic packaging, together with poor waste management systems, causes a valuable loss of material resources [9,10].

The transition from the dominant linear economy to a model grounded in circularity by intention and design can build a new foundation for the packaging sector and its economy [11,12]. The solution to dissociate plastics from environmental pollution should include the redesign of the lifecycle of plastics, products and services, from which no waste is generated or economic value is lost [13–15]. According to several authors, it is more advantageous to produce a sustainable product than to apply an efficient recycling treatment [16,17].

Designers and manufacturers must think together to adapt the design, materials, production processes, and product storage so that the sustainability of the packaging is promoted [1,18]. So far, packaging is not considered by designers as a component of a product. This behavior dissociates the responsibility of its treatment by the manufacturing companies, hindering and compromising the efficiency of the recycling process [4,11].

In 2018, a set of initiatives were made to mitigate the impact of plastics on the environment. The "Plastics Pact" was established by Europe in 2018 as a local and regional initiative to gather the main stakeholders. The objective was to implement solutions to the circular economy of plastics so that zero plastic packaging leaks into the environment could be achieved by 2030. The following goals were set [19].

- Convert all disposable plastic packaging and plastic products into reusable and recyclable;
- Increase at least 25% of the collected capacity and the recycling of plastics used in packaging and disposable products;
- Reduce by at least 20% the need for virgin materials in disposable plastic products and packaging;
- Increase as much as possible the use of recycled plastics, and at least 30% on average in packaging and single-use products.

The directive 94/62/EC, named "Packaging and packaging waste", is the main EU legislation for packaging. This directive provides a set of rules for all packaging types and wastes with the scope of improving the quality of the environment, protecting human health and guaranteeing the functionality of the internal market. Therefore, it requires that member states ensure packaging has a reusable and recoverable design, a minimum weight and volume, and a reduced content of hazardous substances [20]. The "European Strategy for Plastics in a Circular Economy" emerged and identified the current environmental challenges posed by plastics, surrounding production, use, and consumption. This strategy aims for "at least 55% of all post-consumer plastic packaging in the EU to be reusable or easily recycled until 2030" [21,22]. In 2019, the directive EU 2019/904 on the "Reduction of the Impact of Certain Plastic Products on the Environment" was established. The adoption of the single-use plastics directive and the European green agreement of the EU Commission, set a number of restrictive measures that must be achieved until July 2024 [23]. However, to meet these ambitious OECD targets regarding plastic packaging recycling, changes are necessary in the design of these products, the collection system, and even the market demand [24].

Mechanical recycling is the most used method for plastic packaging recycling [25,26]. However, although plastics theoretically have high recyclability and there are collection and recycling systems in place for plastic packaging, the current recycling rates and quality of most recycled materials are low [24]. This is mostly due to the huge diversity of plastics in the packaging flow and also the inability of existing collection infrastructures to support selective collection of high-value plastic packaging [25].

Furthermore, the current contamination of the post-consumer packaging waste stream is so high that to achieve recycled materials with the purity and quality necessary for the application in closed cycles, more efficient separation procedures are required. Naturally, these improvements increase the cost of recycled material, sometimes making it even more expensive than virgin material, thus leading the plastic packing sector to disregard it as a viable option and delaying the transition of the sector to a circular economy [24].

To monitor the transition to a circular economy in products and companies, several tools were developed in recent years [27–29]. Among such tools are the circularity micro-indicators, proposed by several authors in the literature [30–33]. Over 100 micro-level CE indicators are mentioned in 11 literature review papers previously analyzed [34]. These indicators are based on two implicit assumptions [28,33]: (A) the closure of the material Loop at the product level, with the aim of improving the effectiveness and quality of the material for a new cycle; and (B) maximizing the circularity of the material or product to mitigate environmental impacts resulting from the production of virgin raw materials.

Kristensen and Mosgaard [30] selected 30 of those indicators to be the most predominant in measuring nine different CE categories: reuse, resource-efficiency, disassembly, lifetime extension, waste management, multidimensional indicators, end-of-life management, remanufacturing, and recycling. Among those, 28 remain important in the scientific literature, as described in [12,34], but not all of them are relevant to the packaging sector. This is the motto that led to the present work.

In this paper, an analysis of micro-level CE indicators is made to identify the CE micro-indicators that are particularly important to packaging products and companies. In a broad sense, the engagement of the micro-level CE indicators with the CE guiding principles is made together with the relationship between the selected indicators and the Design for X (DfX) approaches that are currently most suitable for plastic packaging. Aiming at highlighting directions and good practices to promote the circularity adoption in the packaging sector, the most common parameters between different calculation methodologies are related to the parameters of DfX approaches.

2. Barriers of Plastic Packaging Recycling

According to the study by Antonopoulos et al. [24] concerning plastic packaging processing companies, the main barriers to recycling post-consumer plastic packaging are technological limitations and the quality of the recovered post-consumer plastic material.

However, there are many other barriers that compromise the efficiency of the recycling process and the quality of the recycled material in terms of modifying its properties and requirements for specific processing techniques.

Currently, HDPE and PET plastic packaging are the most recycled. However, the main challenge lies in using those recycled materials in higher-value applications due to the contamination present in these waste streams as well as the mix of colors, which prevents the recycled material from these wastes from being transparent or white. Plastics of different types contain different melting temperatures. For this reason, if processing mixed polymeric types in bundles, some of them may not melt during the recycling process, while others may degrade, affecting the appearance, performance, and quality of the recovered material and preventing its use in certain final products [25]. However, they can be used in applications with lower value (downcycling), such as hangers, garbage bags, etc. [24]. Investment in technologies that segregate colored plastic waste by color is not yet viable, as market demand cannot justify this approach [25].

Furthermore, plastics have melt flow indexes that have been adapted for specific processing techniques (injection and blow molding, thermoforming, extrusion, etc.), and if recycling together a bundle of plastic packaging waste with products from different processing techniques, the recyclate ends up with a melt flow index that might be inadequate for any conventional technique [25].

Transparent and translucent packaging are currently the most recovered packaging due to their high marketability and flexibility to be pigmented and recycled into new products, thus being the highest-value plastic packaging materials. On the other hand, due to the inability of colored plastics to be dyed in light colors, they are only used to produce darker tones or black, making them difficult to compete with virgin materials. As they are considered materials of lower value, they most often end up being incinerated or landfilled [25].

As contaminants in high-value recycled streams, we can find additives (plasticizers, retardants, antioxidants, acid scavengers, light and heat stabilizers, lubricants, pigments, etc.) and lower-quality materials (multilayer films, etc.). Additives incorporated into the polymeric structure to improve the performance and functionality of polymeric packaging can hamper the quality of the recycled material. Hazardous substances from additives can be released during the recycling process, causing unwanted stains, color changes, or melting problems, or they can be partially retained in the recycling, affecting their final use [24,25]. The fillers' presence in some packages causes them to sink instead of float during separation by density, causing contamination in higher-density material flows [24].

Multilayer films are even more complicated as there is no market for mixed plastic recyclate, and only chemical recycling solutions present great expectations for the future. However, due to the high cost of chemical recycling, it will only be viable if market demand for this type of recycled material increases significantly [35,36].

Considering these barriers, it is imperative to substantially improve collection systems so that it is possible to close the packaging cycle and promote the circularity of these flows. One of the crucially necessary improvements concerns the segregation of high-value polymer types since the composition and purity of the material recovered from post-consumer packaging are the determining factors for its use in the processing of new packaging [24]. Therefore, plastic packaging design needs to urgently evolve to follow the principles of circular design.

3. Circular Packaging

Circular economy comprises several strategies to increase the circularity of a product, namely: designing all stages of materials, products and services from the beginning of their life cycle in order to maximize their useful life as much as possible, and ensuring that no material is wasted [37]. To this end, a product should be reused, repaired, reconditioned, remanufactured or ultimately recycled [38–40], if possible, always benefiting society [41] and adding value [42,43].

Circularity in plastic packaging can be developed and implemented by first prioritizing the elimination/reduction of problematic and disposable packaging in circulation through redesign and new supply and reuse models for these products. Also, decoupling the consumption of finite resources and the prohibition of dangerous products for the production of new packaging to the detriment of the implementation of reusable, recyclable or compostable resources are principles to consider for obtaining circular plastic packaging [42].

The application of micro-level circularity indicators can be extremely useful in improving the circularity of products, as they help in the design of new products, providing decision-makers and managers in the decision-making process with information on how to improve the circularity of these products [43]. Such tools can also assist in the preparation of internal company reports by elucidating the level of compliance with legal standards by the company and its products [44]. Furthermore, these indicators can be used to compare different product ranges and demonstrate to customers the circular economy progress of a given product compared to others on the market [45].

However, this wide range of indicators was developed ad hoc [38], presenting different purposes, methodologies and metrics [39,40] and as the Circular Economy is a multifaceted concept, the results of these indicators generate different interpretations [27]. That said, the great diversity of indicators and the ambiguity of their objectives make it difficult to choose which are most appropriate in a specific context or product [43], especially in the packaging sector. The current work addresses and attempts to overcome this difficulty.

Several packaging brands on the market are modifying their production logic to move towards a circular economy through the development of edible or biodegradable packaging or by replacing liquid products with solid ones that do not require packaging [46]. In 2020, the packaging directive was updated to reduce the environmental impact caused by plastics, and a restricted set of measures were enacted, with results obtained by 31 December

2024 [47]. Also in the same year, the global commitment progress report was issued, which states that despite the progress achieved, it will be necessary to accelerate global progress to achieve the 2025 goals [48]. The most significant progress in this commitment was the incorporation of recycled content in plastic packaging and the elimination of polymers and problematic substances identified in packaging such as PS, PVC and carbon black. However, progress in increasing packaging recyclability and reducing single-use packaging has been more limited [48].

Therefore, there is still a need to improve resource efficiency and promote the circularity of plastic packaging. For the goals of a circular economy to be successfully achieved, it is still necessary to [49]:

- Accelerate research into alternative raw materials;
- Periodically update the life cycle inventory;
- Include new data on the circularity of packaging;
- Develop eco-design guidelines for plastic packaging;
- Support the standardization of quality standards for plastics;
- Innovate and standardize to increase the recycling of polyolefins;
- Harmonize quality standards for polymeric waste, testing methods for recycled polymers and certification of recycling operations;
- Innovate and develop packaging-free markets to encourage the reuse of packaging;
- Stimulate innovation in recycling and reuse technologies;
- Develop technologies to recycle PS/EPS back into their original products;
- Improve waste collection and sorting systems.

4. DfX Approaches Relevant for Sustainable Packaging Products

Aside from the role that circularity micro-indicators play in the transition to a circular economy in the packaging sector, it is extremely important to rethink the design concept, acting on the earliest stages of the process, using "Design for X" (DfX) approaches [50]. The idea is to revise the product design and production processes before the product is made, allowing detection of design problems without excessive costs and delays [51,52]. The DfX techniques are thought to improve the design process from a circular perspective [53]. Most of their focus the attention on the design process through circular metrics and evaluations, but few of them have the objective of supporting decision-making along the design process [53]. Although employing DfX approaches increases design time, it ends up decreasing manufacturing time, as well as causing problems that often emerge at later stages [50,51]. Design for X approaches is vast [54]; however, only some are particularly suitable for packaging design.

Lee and Lye proposed the design for packaging approach [55], combining the principles of two other existing DfX approaches, namely design for environment (DfEnv) and design for assembly (DfA), both of which are described in more detail below. The authors argue that incorporating DfEnv principles mitigates the potential impact of practices and materials that may be negative to the environment and overall, can improve the product packaging process compared to standard DfA [55].

The DfEnv approach improves packaging's environmental performance while reducing costs, since it aims to reduce waste generation and energy consumption, minimize transport, and use of materials and energy recovered throughout the product life cycle [56,57]. In a study carried out by [58], a decrease of approximately 30% in the environmental impact of a new sustainable packaging was achieved through the application of DfEnv principles. This approach involves the development of products with environmentally friendly materials, fewer resources, and less packaging. Therefore, the packaging solutions are easy to recycle, reuse or upgrade [56,57]. The DfEnv strategy to reduce packaging argues that packaging should be reclaimed, integrating biodegradable, recovered, or recycled materials, and belong to the product itself [57].

The DfA defends a product that is simple in its nature, with few parts and simple operation, so that it is easier and faster to assemble with few mistakes [1,52,59]. The following principles are defended by DfA: minimize the number of parts, build the fasteners and connectors into the part itself, design using Commercial Off-the-Shelf (COTS) parts and minimize the use of different tools, prevent incorrect assembly of product parts, pay attention to product symmetry, identify the parts as right or left-handed parts, and optimize their tolerance [60,61].

The CE principle of reducing packaging dismissal forces it to become circular by extending its lifecycle through reuse or remanufacturing and maintaining its reliability along successive cycles [62]. The "design for manufacturing and assembly" (DfMA), "design for reliability" (DfR), and "design for sustainability" (DfS) support the DfX approach for packaging circularity [53]. The DfMA combines two DfX approaches: the DfA and "design for manufacturing" (DfM) [53,63]. The DfM foresees that parts composing the product can be made from common and maturate materials and processes that support the general design intention [52,64]. In addition, designed parts or products must be manufactured at lower costs. Their principles are similar to the DfA, but they add the creation of modular designs with multifunctional, multiuse and easy handling parts and the minimization of the assembly direction to facilitate the manufacturing and remanufacturing of the product [65,66].

The "design for sustainability" (DfS) approach, in addition to promoting efficiency in the use of resources, is concerned with people's well-being and places the sustainability of the planet at the forefront [67,68]. Its principles are low environmental impact during production, reduction of the number of consumed resources, reduction of the amount of pollution emitted, increasing collection, and improving the recycled materials to produce new packaging [52]. The DfS also encourages people to think of nature as a model, mentoring and developing products with biomimicry designs that fit into the earth's ecosystem [68–70].

In the "Design for Reliability" (DfR) approach, packaging should be tested through risk analysis, such as FMEA (failure modes and effects analysis), VOC (voice of the consumer), and DOE (design for experiments), and learning from mistakes from similar packaging products. If an evaluation is made of already existing packages and faults are identified, it is possible to avoid mistakes in the production of new packages [71,72].

Ergonomics are important characteristics for packaging. Therefore, design for ergonomics (DfE) is an approach to defending packaging that is adapted to the user's body, a more friendly and ergonomic product, having in mind the user's physical attributes, and signaling the correct use of packaging [52,73,74]. If the packaging has suitable ergonomics, it should induce correct use, and the consequent reduction of the chance of it becoming damaged promotes its reuse [73–75].

5. Methods

This work considers the 28 micro-level CE indicators that remain important in the literature and were reviewed in a previous paper [34]. These 28 micro-indicators resulted from the evaluation of 11 literature reviews obtained through a bibliographical search in the Web of Science and Scopus databases, within the scope of micro-level circularity indicators. This research resulted in a total of more than 100 circularity micro-indicators, which found out which indicators were most frequently referenced [34].

In Section 6.1, the micro-indicators that can be used to assess the circularity level, specifically of plastic packaging products, are identified. The selection of the micro-indicators relevant for the packaging sector was made in collaboration with personnel responsible for product development, production and management departments of a plastic packaging product manufacturer, plus a team of four polymer engineers with competences in circular economy and LCA. The collaboration with packaging manufacturers helped us gather information about the availability of the data required to calculate these indicators. The engineers, based on their knowledge and experience about the life cycle of plastic packaging, made their contribution by analyzing the calculation methodologies for each indicator, evaluating the feasibility of the calculations and determining whether each indicator properly reflected the principles of the circular economy in its approach.

However, during this selection process, we found that the relevance of each indicator will depend on the product under analysis and the type of input expected by the company, depending on which aspects of circular economy they want to improve.

Therefore, to help packaging manufacturers and companies in circularity indicators' selection to assess the circularity of their products, we developed a series of comparative analyses, which resulted in tools that can be used by companies in decision-making.

To know how far the CE micro-indicators are truly in line with these CE guiding principles provided by the Ellen MacArthur Foundation and defined by the new plastic economy initiative, the 18 micro-indicators selected as relevant for packaging are grouped in their CE focus categories and linked to a guiding principle for circular economy (Section 6.2). To group the indicators and link them to CE guiding principles, we analyzed the calculation methodology for each indicator and verified which of these contained parameters that were in line with these principles. This analysis can aid companies in selecting the indicators for evaluating the circularity of a given product, bearing in mind the guiding principle on which they intend to focus their study.

As DfX approaches can guide product design to be more in line with the principles of a sustainable and circular product, in Section 6.3, we carry out a comparative analysis between the circularity indicators relevant to packaging and the guidelines of the most applicable DfX approaches. The grouping of these indicators was carried out according to the same approach as the comparative analysis of the CE guiding principles.

Finally, as micro-indicators assess circularity through the input of several parameters, many of which are used in different circularity indicators, in Section 6.4, patterns are analyzed to identify which are the most common parameters among all CE micro-indicators relevant to packaging. The featured parameters are those that most frequently appear in indicator calculation methodologies. This study highlights which specific actions and improvements can have a broader impact on different aspects of circularity.

6. Results

This section concerns the circularity micro-indicators we considered relevant and, among those, the most relevant for packaging products, and the results obtained for each comparative analysis. Aside from presenting in detail the analysis performed for each comparative analysis, the results are discussed within the framework of circularity guiding principles and Design for X approaches.

6.1. Circularity Micro-Indicators Relevant for Packaging

In a general view, if the most common packaging is considered, e.g., films, containers, and discarded packages, it is easy to understand that disassembly is not applicable to those products. Also, if packaging with more than one component or multilayer is considered, materials will not be separated at EoL. Furthermore, for the majority of plastic packaging products, there are no take-back collection systems to promote the reuse or remanufacturing of plastic packaging. For these reasons, the CE indicators focused on Disassembly are generally not applicable to the packaging industry, and, depending on the specific packaging product, many indicators in the EoL Management, Reuse and Remanufacture categories may also not be applicable.

The most relevant micro-indicators for the packaging sector are the ones represented in bolt and underlined in Figure 1. These are the Material Circularity Indicator (MCI) [76], Recycling Desirability Index (RDI) [77], Reuse Potential Indicator (RPI) [78], Circularity Calculator (CC) [79], Material Reutilization Score (MRS) [80], Circular Economy Index (CEI) [81], Product-level Circularity Metric (PLCM) [82], Longevity Indicator (LI) [83], Model of Expanded Zero Waste Practice (EZWP) [84], Value-Based Resource Efficiency Indicator (VRE) [85], Circularity Design Guidelines (CDG) [86], and Circular Economy

Indicator Prototype (CEIP) [87]. The majority of these indicators are in the Recycling, Lifetime extension, Waste Management, and Multidimensional Indicators categories.

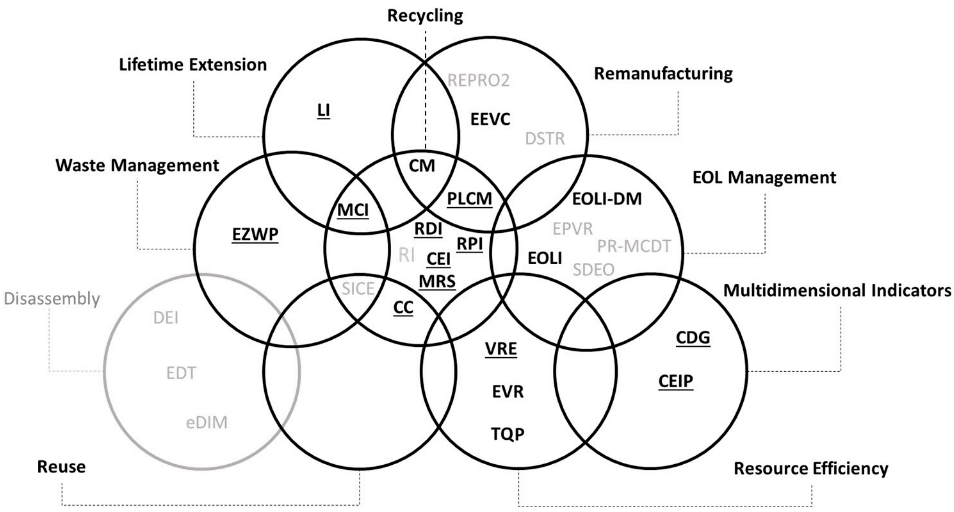

Figure 1. Micro-indicators relevant for estimating the circularity of plastic packaging products (the classification in categories is adapted from Kristensen and Mosgaard, 2020). Micro-indicators in bold black text and underlined are the most relevant, in bolt black text are somewhat relevant, while greyed text ones are not relevant for the packaging sector. CC: Circularity Calculator, CDG: Circularity Design Guidelines; CEI: Circular Economy Index, CEIP: Circular Economy Indicator Prototype, CM: Combination Matrix, DEI: Disassembly Effort Index, DSTR: Decision Support Tool for Remanufacturing, eDIM: Ease of Disassembly Metric, EDT: Effective Disassembly Time, EEVC: Eco-efficient Value Creation, EOLI: End-of-life Index, EOLI-DM: End-of-life Indices (Design Methodology), EPVR: End-of-use product value recovery, EVR: Eco-cost/value Creation; EZWP: Model of Expanded Zero Waste Practice; LI: Longevity Indicator; MCI: Material Circularity Indicator, MRS: Material Reutilization Score, PLCM: Product-level Circularity Metric, PR-MCDT: Product Recovery Multi-criteria Decision Tool, RDI: Recycling Desirability Index, REPRO2: Remanufacturing Product Profiles, RI: Recycling Indices, RPI: Reuse Potential Indicator, SDEO: Sustainable design and end-of-life options, SICE: Sustainability indicators in Circular Economy, TQP: Typology for Quality Properties and VRE: Value-Based Resource Efficiency.

Other less relevant micro-indicators are Eco-efficient Value Creation (EEVC) [88], Combination Matrix (CM) [89], End-of-life Index (EOLI) [90], End-of-life Indices (Design Methodology) (EOLI-DM) [91], Eco-cost/value Creation (EVR) [88], and Typology for Quality Properties (TQP) [92]. The extensive list of source references and the definition of the micro-indicators were previously presented in [34].

Regarding MCI, it measures how restorative the material flows of a product are, considering the recycled content linked to the waste and its usefulness [76], as shown in Equation S.1 in the Supplementary Information file. This indicator is very useful for checking whether the flow of materials involved in the product is closer to a linear economy of extraction-production-use-disposal or a circular economy.

In general, the plastic materials used in packaging applications are collected and separated from municipal solid waste (MSW) for further recycling. The RDI is essential to the packaging sector because this indicator evaluates how desirable the recycling process is for a product [77]. This indicator varies between 0 and 3 and is calculated by Equation S.2 in the Supplementary Information file.

Material wastes provided by plastic packaging products have a variety of polymers that are difficult to separate, and therefore the properties of recycled materials are sometimes compromised, where the RPI indicator can be very useful. This micro-indicator evaluates how similar the recovered materials are to waste or a resource and whether any waste material recovery process is economically viable in comparison to their disposal in landfills [78] through Equation S.3 in the Supplementary Information file. In addition, the difficulty in separating the materials that make up packaging sometimes makes the recycling process economically unfeasible compared to the production of a new, totally virgin product. The CEI micro-indicator evaluates the recycling efficiency in economic terms and compares this value with the value necessary to produce a new product [81], as shown in Equation S.4 in the Supplementary Information file.

After obtaining the plastic recycled from packaging waste collected from a specific collection system, this material can be used to produce new plastic packaging. The CC is an online tool that calculates the recycled content of a product, considering the contributions of recycled content through the original product and recycled content through recycling in a closed loop, thus assessing the potential value captured by circular business models [30,79].

Recycling processes are frequent in packaging plastic materials, as well as the use of biodegradable, recycled or compostable materials. The MRS micro-indicator evaluates the material involved in the product and if it can be recycled at EOL [80] through Equation S.5 in the Supplementary Information file.

Packaging products such as containers for water, cleaning detergents, and personal hygiene products, among others, beyond the recycling process, can be recirculated by the user in multiple cycles through refilling systems. The PLCM and LI are two micro-indicators that evaluate this aspect of circularity. The PLCM is based on the relationship between the economic value of the recycled product and the total economic value of the product [82]. On the other hand, the LI measures the time that the material is retained in the product cycle, providing for multiple reuse and recycling cycles and decreasing natural resource exploration [83]. The equations to calculate this indicator are provided in the Supplementary Information file (Equations (S.6)–(S.8)). To evaluate circularity in the social dimension and monitor employees' engagement with zero-waste practices, the EZWP [84] is a very useful micro-indicator. To achieve circularity, resources associated with the production process must also be used in a sustainable way, in terms of which the VRE [85] micro-indicator can be employed to consider the value of non-sustainable inputs that concern the product (energy, materials, labor, components, and others), as per Equation S.8 in the Supplementary Information file.

Sometimes, a company may need to make quick decisions and is unable to collect data to calculate circularity (or that data might still not exist for a new product being planned). In this scope, the CDG [86] and CEIP [87] indicators are ideal for providing guidance on improvements they can make to their product and at which stages of the life cycle the product should be further improved to achieve greater circularity.

Although CM, EVR, EOLI, EOLI-DM, and TQP are important micro-indicators for estimating the circularity of a packaging product, they present complex calculation methodologies, some of which require an LCA to be carried out, making it sometimes difficult to gather the data required for their calculation, which makes these indicators less relevant for this application sector.

The micro-indicators depicted in gray in Figure 1 were considered to not be relevant for the packaging industry. The Sustainability indicator in CE (SICE) [93] was not considered because it calculates the circularity through parameters such as the amount or value of remanufactured or reusable material and also involves parameters like functionalities achieved with little configuration change in the product's components, and the majority of packaging products do not have collection systems implemented for reuse or remanufacturing. Packaging products are not designed for disassembly, so these indicators (DEI, EDT and eDIM) do not fit into the packaging sector. Also, most scenarios of reuse are unfeasible in packaging, such as those of food protection films or product seals, since they are destroyed by the consumer at the moment of extracting the stored product. Thus, indicators like the Designed method for end-of-use product value recovery (EPVR) [94], Remanufacturing Product Profiles (REPRO2) [95], the Product Recovery Multi-criteria Decision Tool (PR-MCDT) [96], and the Decision Support Tool for Remanufacturing (DSTR) are also not considered suitable for packaging products. Last, the Recycling Indices (RI) [97] and Sustainable Design and End-of-Life Options (SDEO) [98] feature a very high level of detail and complexity, showing apparent impracticality of application in a common industrial environment, making their calculation unfeasible in assessing the circularity of plastic packaging.

In conclusion, a vast number of micro-indicators are already available in the literature. However, for the plastic packaging sector, a selection of 18 micro-indicators was made that are mainly directed to the categories of recycling, lifetime extension, waste management and multidimensional indicator categories, 12 of which were considered highly relevant for this sector.

6.2. Engaging Micro-Level Indicators to CE Focus Categories and Guiding Principles

To further the implementation of circular economy in the packaging sector, it is necessary to follow some guiding principles, namely: (1) to eliminate unnecessary packaging through design reformulation and new delivery models; (2) to reduce discarded packaging and promote reuse models where relevant; (3) to implement 100% reusable, recyclable or compostable plastic packaging; (4) to disengage plastic materials produced with finite resource consumption; and (5) to ban dangerous chemical products in plastic packaging [19].

As shown in Figure 2, the guiding principles associated with most packaging micro-indicators (only among the 18 indicators identified as relevant for the packaging sector) are "the reduction of discharged packaging and implementation of reuse models where relevant" (circa 78% of the indicators, meaning 14 out of the 18 relevant indicators) and "the implementation of 100% reusable, recycling, or compostable plastic packaging" (circa 44% of the indicators).

CE Focus Categories	Eliminate the unnecessary packaging through design reformulation and new delivery models	Reduce discharged packaging and implement reutilization models where relevant	Implement 100% reusable, recycling or compostable plastic packaging	Disengage plastic material produced with finite resource consumption	Prohibit dangerous chemical products in plastic packaging
Recycling	**CC**	**RDI, RPI, CEI**, CM, **MCI, CC, PLCM**	**CEI, MRS, MCI, CC**	**MRS, MCI**	**RDI**
Lifetime Extension		**LI**, CM, **MCI**	**MCI**	**MCI**	
Waste Management	**EZWP**	**EZWP, MCI**	**EZWP, MCI**	**MCI**	**EZWP**
Reuse	**CC**	**CC**	**CC**		
Resource Efficiency	**VRE**, EVR	EVR	**VRE**, EVR	**VRE**, EVR	**VRE**, EVR, TPQ
Multidimensional Indicators	**CEIP**	**CEIP**	**CEIP**	**CDG, CEIP**	**CDG, CEIP**
EOL management	EOLI-DM	EOLI, EOLI-DM			
Remanufacturing	EEVC	EEVC, CM, **PLCM**			

Guiding Principles

Figure 2. Mapping the position of the CE micro-indicators on the CE focus categories and the guiding principles implemented in each indicator. The most relevant indicators for the plastic packaging sector are marked in bold.

CE focus categories such as "recycling", "waste management", "resource efficiency", and "multi-dimensional indicators" contain indicators that are transversal to all the guiding principles. Special attention should be given to CEIP, which is transversal to all circular economy principles, and also to CC, MCI, EZWP, and VRE, which approach at least three guiding principles each. These are considered the best indicators for circularity calculation in packaging products, given their emphasis on factors such as the amount of waste recovered, the cost of waste recovery through EoL options (reuse, reform, recondition, reuse and, finally, recycle), and the amount of reused, recycled, bio- or compostable material incorporated into the product.

Some other guiding principles, such as "eliminate the unnecessary packaging through design reformulation and new delivery models" (linked to about 39% of the indicators), "disengage plastic material produced with finite resource consumption" (circa 33% of the indicators), and "prohibit dangerous chemical products in plastic packaging" (circa 39% of the indicators), are much less discussed. The reason is related to the current plastic packages being made of plastics coming from finite, non-renewable resources with additives or multilayered solutions for better properties to maintain the integrity of the product until the final consumer. Moreover, the current business model implemented in the packaging sector does not promote reuse or take-back collection systems, which would return these packages to the manufacturing companies.

6.3. Relationship between Packaging Micro-Level CE Indicators and DfX Approaches

In Figure 3, the CE micro-indicators selected as relevant for the packaging sector are classified in terms of their alignment to the DfX approaches previously described. Most of the indicators exhibit principles that are framed by the DfEnv (circa 94%, meaning 17 out of 18 relevant indicators) and DfS (circa 89% of the indicators) approaches, perhaps due to the simple fact that both relate to efficient use of resources and the reduction of the impact caused on the planet. Fewer micro-indicators can be correlated to the DfMA and DfR approaches (circa 44% and 50% of the indicators, respectively), and none follows the DfE approach. The DfMA approaches are included mainly in the indicators related to EoL management, Resource efficiency and Remanufacturing categories. These micro-level indicators focus their circularity calculations on the evaluation of the product functionality, the ease of handling parts, the selection of common and mature manufacturing processes, the selection of fasteners and tools necessary to assembly the product with few mistakes, more efficiency and low emissions. For these micro-indicators, if a product is easily assembled and is environmentally friendly during its production and lifespan, it is easy to repair, refurbish or recycle its parts and materials. That allows the product to return to the system. The DfR is revealed in most indicators of the resource efficiency and multidimensional indicator categories because the micro-indicators of these CE categories allow the designers to estimate the product's behavior during its lifespan. It gives them the possibility to identify the mistakes involved, redesign the product, and increase its circularity.

CE Focus Categories	Design for environment (DfEnv)	Design for Manufacturing and Assembly (DfMA)	Design for Reliability (DfR)	Design for Ergonomy (DfE)	Design for Sustainability (DfS)
Recycling	**RDI, RPI, CEI, MRS, CC, CM, MCI, PLCM**	**MCI**, CM, **PLCM**	**RDI, MRS**		**RDI, RPI, CEI, MRS, CC, CM, MCI, PLCM**
Lifetime Extension	**LI**, CM, **MCI**	**MCI**			**LI**, CM, **MCI**
Waste Management	**MCI**	**MCI**			**EZWP, MCI**
Reuse	**CC**				**CC**
Resource Efficiency	**VRE**, EVR, TPQ	**VRE**, EVR, TPQ	**VRE**, EVR, TPQ		**VRE**, EVR, TPQ
Multidimensional Indicators	**CDG, CEIP**	**CDG**	**CDG, CEIP**		**CDG, CEIP**
EOL management	**EOLI, EOLI-DM**	**EOLI, EOLI-DM**	**EOLI-DM**		
Remanufacturing	EEVC, CM, **PLCM**	EEVC, CM, **PLCM**	EEVC		EEVC, CM, **PLCM**

DfX Approaches

Figure 3. Mapping the correlation between CE micro-indicators in terms of their CE focus categories and alignment to Design for X approaches. The most relevant indicators for the plastic packaging sector are marked in bold.

The CE focus categories of Resource efficiency, Multidimensional indicators and Remanufacturing are those where the indicators are found in most DfX approaches. The indicators belonging to these categories consider the efficiency of resource consumption (water, energy, and labor) during manufacturing, transport and logistics; the dematerialization of the products; the amount of waste generated; the impacts and costs of EoL options; and the economic value returned through the recovery of the product by calculating the circularity of a single product. This analysis reveals that MCI, VRE, CDG, CEIP and PLCM are very developed indicators in terms of DfX approaches, which are important for the circularity calculations in plastic packaging products.

Considering the characteristics of plastic packaging and according to the previous analysis, it can be concluded that the DfX to design a circular and sustainable packaging product are DfEnv, DfMA, and DfS.

6.4. Principles for CE and Its Relationship with Micro-Level Indicators and DfX Approach

CE micro-indicators calculate the product's circularity through the input of several parameters. They can be grouped into eight categories that evaluate different CE principles, namely: sustainability of raw material input, addition of non-harmful additives, prevention of waste production, extension of product life, prevention of unrecoverable waste, waste recovery, easy separation and recycling efficiency.

In Figure 4, it is possible to see that 83% of the packaging-relevant indicators (15 out of the 18 relevant CE micro-indicators) require inputs related to waste recovery. The indicators included in this group require data such as the amount of material collected for recycling or incineration, the value returned to the cycle through the recycling process, and/or the cost of waste recovery to calculate the circularity of a product.

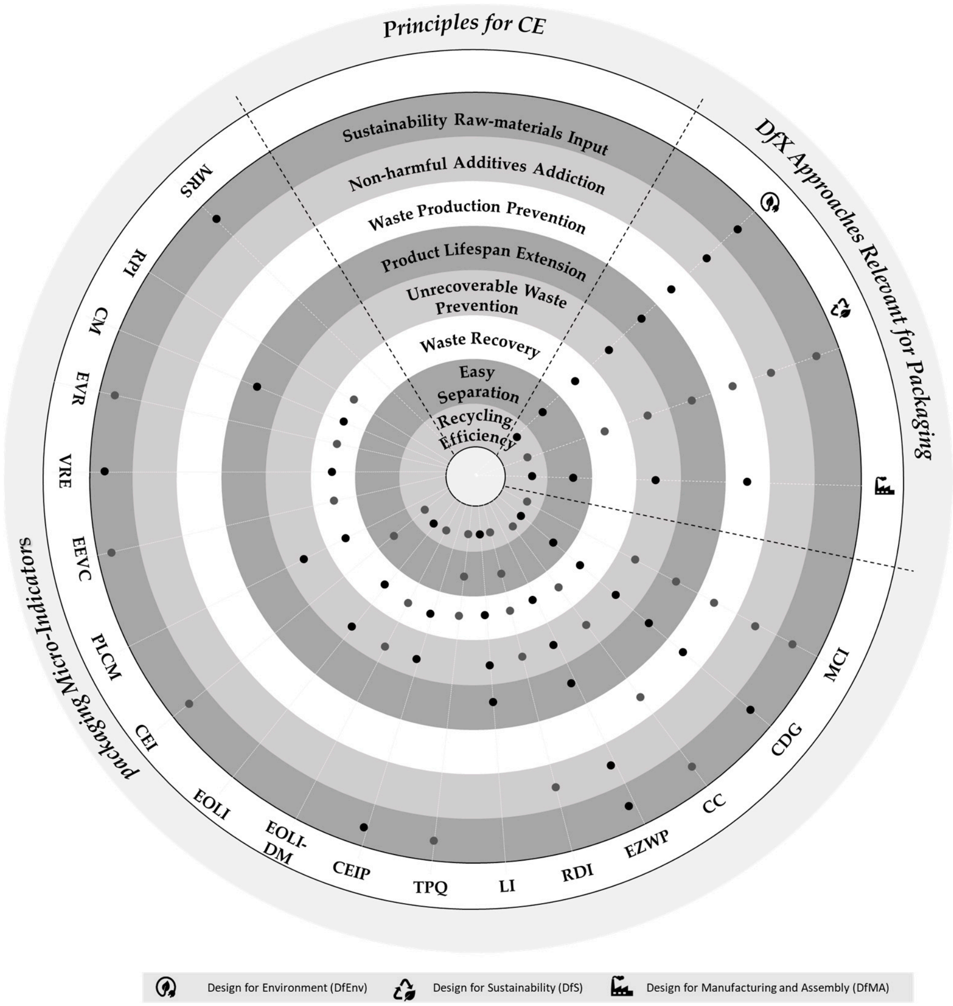

Figure 4. Principles of CE involved in the calculation methodology of CE micro-indicators and their relationship to key DfX approaches.

The second most common group of parameters (in circa 61% of the indicators) is related to the sustainability of the input of raw materials. This group involves inputs such as the amount of recycled, biodegradable, or compostable material and the cost or value of the raw material used in the product.

The third most common group of inputs among packaging indicators (circa 56% of the indicators) is related to the prevention of irrecoverable waste. The indicators involved in this group require data such as the cost of the waste recovery process (such as reuse, remodeling or recycling) and the amount of material recovered.

Half of the indicators selected as relevant for packaging (nine CE micro-indicators) also require inputs related to recycling efficiency, such as the percentage of efficiency of the recycling process to recycle an end-of-life product or the quantity of product that it is possible to recycle or recirculate.

However, inputs related to the addition of non-harmful additives (circa 17% of the indicators), prevention of waste production (circa 17% of the indicators), extension of product life (circa 28% of the indicators), and easy separation (circa 22% of the indicators) are not common among the indicators selected as relevant to the packaging sector. These parameters are more specific and therefore only relevant in some aspects of circularity.

Figure 4 also shows the relationship between these inputs and the most relevant Design for X strategies for the packaging sector.

The inputs related to recycling efficiency, prevention of irrecoverable waste, and prevention of waste production follow principles that are defended by the three most relevant DfX approaches for plastic packaging (DfEnv, DfS and DfMA), namely principles such as reducing the diversity of materials, using compatible materials, and employing mature processes.

7. Good Practices and Concluding Remarks

As circularity indicators are a fairly recent and ad hoc development in the academic community, they present a plethora of approaches, calculation methodologies and metrics. Furthermore, these indicators are not described in the literature as sectoral indicators, making it difficult to understand the relevance of their application to a given product, for example, by applying them specifically to the packaging sector. It is in this aspect that the present work becomes innovative. Based on the vast literature available on the circularity of products, a selection of micro-level CE indicators for the plastic packaging sector was made. However, it is important to highlight that this selection was carried out based on the knowledge and experience of the parties involved in this work, where a different panel of experts or a focus on a different type of packaging could have led to different indicators being prioritized.

This article also provides tools that assist designers and managers in selecting which indicators to use to evaluate the progress of a given package in terms of implementing circular economy principles and DfX approaches, considering the parameters involved in the calculation methodology for each indicator.

This is also expected to be a helpful tool for designers and companies producing plastic packaging to guide the development of more circular packaging products.

From their relation to the guiding principles for CE transition and DfX approaches, it was possible to identify guidelines and good practices to improve the circularity of packaging products. Figure 5 summarizes these guidelines and good practices for increasing circularity in packaging products. For each of the guidelines mentioned, the DfX approaches that are best applied to plastic packaging are identified.

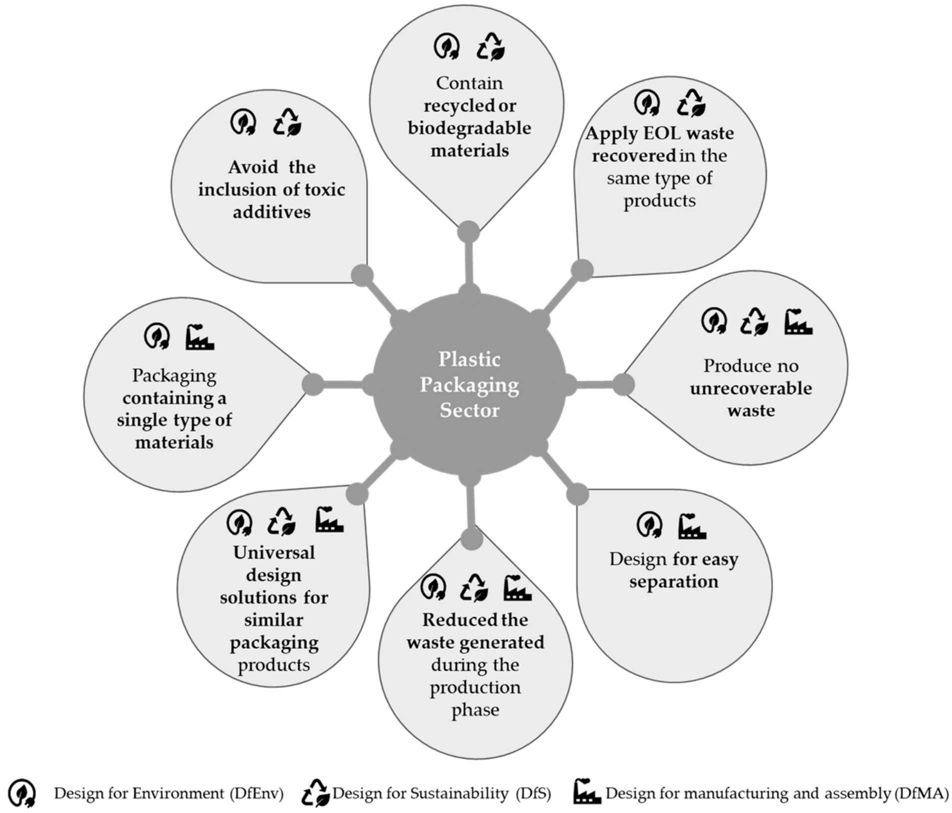

Figure 5. Good practices for improving the circularity of the plastic packaging sector.

In conclusion, circularity indicators are useful tools for assessing risks and identifying opportunities for improvement. However, the knowledge base associated with most of the available indicators is not sufficient for a clear and reliable assessment [99,100], as the purpose of the indicator is not always clear [27], and results can be interpreted in various ways, which promotes misleading conclusions [31].

For plastic packaging processors to adopt the application of circularity indicators in their product development and quality control processes, there is a need to make these metrics credible and relevant to communicate to customers the circularity of their products compared to others on the market. For this, it is necessary to standardize the indicators.

Nevertheless, our analyses, through studying in depth the methodology behind each indicator relevant to packaging, show that there are actions that clearly promote circularity in this sector, which sometimes goes against the government measures currently implemented. This is because, even if packaging incorporates more sustainable plastic materials (biological, compostable or recycled), proper packaging collection and recovery systems are not yet in place, leading to low-performance recyclates.

Thus, regulatory policies would benefit from the results obtained in this work and the previously proposed guidelines, namely:

- Establish measures that restrict the tipology of polymeric materials allowed per packaging type.
- Encourage the incorporation of recycled or biological material, taking measures to reduce the market cost of these materials, for example, through tax incentives.
- Prohibit the use of toxic elements, such as harmful additives.
- Encourage product developers to consider their choices according to the possibilities of end-of-life treatments available, so that unnecessary waste is not generated.
- In packaging that requires more than one material, encourage product developers to design packaging that can easily separate the different materials without contaminating the individual components.

- Develop more efficient recycling systems and new waste streams, mainly for bio-based and degradable packaging, so that they do not contaminate existing waste streams (and implement educational programs for the population to properly dispose of them in these new streams).
- Packaging design should follow universal design solutions for the same product between different brands to facilitate the recycling process.

Finally, recycling is not the only solution for reducing packaging plastic waste pollution. Producers and consumer associations should create collection locations and/or promote packaging reuse whenever possible, for example, by allowing refills when possible and implementing take-back systems.

Through the increased implementation of circular economy principles and evaluating their progress with circularity micro-indicators, the packaging sector can shift towards a sustainable (and more circular) future, vital for modern society.

In our future work, we will identify case studies with industrial partners to validate and demonstrate the practical application of this selection of relevant indicators for the packaging sector.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16052182/s1.

Author Contributions: Conceptualization, R.S.; Data curation, R.S. Investigation, J.M. and C.I.M.; Methodology, J.M.; Resources, R.S.; Supervision, C.I.M. and R.S.; Writing—original draft, J.M.; Writing—review and editing, C.I.M. and R.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Portuguese Foundation for Science and Technology, through projects UIDB/05256/2020 and UIDP/05256/2020, and Ph.D. grant UI/BD/150827/2021 (J.M.).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Polymer Families	
ABS	Acrylonitrile Butadiene Styrene
HDPE	High Density Polyethylene
LDPE	Low Density Polyethylene
PET	Polyethylene Terephthalate
PP	Polypropylene
Circularity Micro-Indicators	
CC	Circularity Calculator
CDG	Circularity Design Guidelines
CEI	Circular Economy Index
CEIP	Circular Economy Indi-cator Prototype
CM	Combination Matrix
DEI	Disassembly Effort Index
DSTR	Decision Support Tool for Remanufacturing
eDIM	Ease of Disassembly Metric
EDT	Effective Disassembly Time
EEVC	Eco-efficient Value Cre-ation
EOLI	End-of-life Index
EOLI-DM	End-of-life Indices (Design Methodology)
EPVR	End-of-use product value recovery

EVR	Eco-cost/value Creation
H EZWP	Model of Expanded Zero Waste Practice
LI	Longevity Indicator
MCI	Material Circularity In-dicator
MRS	Material Reutilization Score
PR-MCDT	Product Recovery Multi-criteria Decision Tool
RDI	Recycling Desirability Index
REPRO2	Remanufacturing Product Profiles
RI	Recycling Indices
RPI	Reuse Potential Indicator
SDEO	Sustainable design and end-of-life options
SICE	Sustainability indicators in Circular Economy
TQP	Typology of Quality Properties
VRE	Value-Based Resource Efficiency
Design for X Approches	
DfX	Design for Excel-lence
DfA	Design for Assem-bly
DfEnv	Design for Envi-ronment
DfE	Design for Ergo-nomics
DfM	Design for Manu-facturing
DfMA	Design for Man-ufacturing and Assem-bly
DfR	Design for Reliabil-ity
DfS	Design for Sustain-ability
Others	
CE	Circular Econo-my
COTS	Commercial off-the-shelf
DOE	Design of Ex-periments
EOL	End of life
EU	European Union
FMEA	Failure Mode and Effects Analysis
LCA	Life Cycle Analysis
MSW	Municipal solid waste
VOC	Voice of the Customer

References

1. Betancur-Muñoz, P.; Osorio-Gómeza, G.; Martínez-Cadavid, J.F.; Duque-Lombana, J.F. Integrating design for assembly guidelines in packaging design with a context-based approach. *Procedia CIRP* **2014**, *21*, 342–347. [CrossRef]
2. Pascall, M.A.; DeAngelo, K.; Richards, J.; Arensberg, M.B. Role and Importance of Functional Food Packaging in Specialized Products for Vulnerable Populations: Implications for Innovation and Policy Development for Sustainability. *Foods* **2022**, *11*, 3043. [CrossRef]
3. Plastics Europe. *Plastics–The Facts 2022*; Plastics Europe: Brussels, Belgium, 2022.
4. Ajwani-Ramchandani, R.; Figueira, S.; Torres de Oliveira, R.; Jha, S.; Ramchandani, A.; Schuricht, L. Towards a circular economy for packaging waste by using new technologies: The case of large multinationals in emerging economies. *J. Clean. Prod.* **2021**, *281*, 125139. [CrossRef]
5. Mudgal, S.; Lyons, L.; Bain, J.; Dias, D.; Faninger, T.; Johansson, L.; Phil, D.; Shields, L.; Bowyer, C. *Plastic Waste in the Environment—Final Report*; EU: Maastricht, The Netherlands, 2011.
6. Zhu, Z.; Liu, W.; Ye, S.; Batista, L. Packaging design for the circular economy: A systematic review. *Sustain. Prod. Consum.* **2022**, *32*, 817–832. [CrossRef]
7. Plastics Europe. *Plastics the Fast Facts 2023: A Review on Plastic Contributions to European Economy*; Plastics Europe: Brussels, Belgium, 2023.
8. Dintcheva, N.T.; Infurna, G.; D'Anna, F. End-of-life and waste management of disposable beverage cups. *Sci. Total Environ.* **2020**, *763*, 143044. [CrossRef]
9. Diggle, A.; Walker, T.R. Environmental and Economic Impacts of Mismanaged Plastics and Measures for Mitigation. *Environments* **2022**, *9*, 15. [CrossRef]
10. Johansen, M.R.; Christensen, T.B.; Ramos, T.M.; Syberg, K. A review of the plastic value chain from a circular economy perspective. *J. Environ. Manag.* **2022**, *302*, 113975. [CrossRef]
11. Casarejos, F.; Bastos, C.R.; Rufin, C.; Frota, M.N. Rethinking packaging production and consumption vis-à-vis circular economy: A case study of compostable cassava starch-based material. *J. Clean. Prod.* **2018**, *201*, 1019–1028. [CrossRef]

12. Matos, J.; Martins, C.I.; Simoes, R. Circularity Micro-indicators for plastic packaging. In Proceedings of the 2nd International Conference on Circular Packaging—2nd CPC, Slovenj Gradec, Slovenia, 9–10 September 2021; pp. 187–192.
13. Vermeulen, I.; Van Caneghem, J.; Block, C.; Baeyens, J.; Vandecasteele, C. Automotive shredder residue (ASR): Reviewing its production from end-of-life vehicles (ELVs) and its recycling, energy or chemicals' valorisation. *J. Hazard. Mater.* **2011**, *190*, 8–27. [CrossRef] [PubMed]
14. Badia, J.D.; Gil-Castell, O.; Ribes-Greus, A. Long-term properties and end-of-life of polymers from renewable resources. *Polym. Degrad. Stab.* **2017**, *137*, 35–57. [CrossRef]
15. Dobrotă, D.; Dobrotă, G.; Dobrescu, T. Improvement of waste tyre recycling technology based on a new tyre markings. *J. Clean. Prod.* **2020**, *260*, 121141. [CrossRef]
16. Ellen MacArthur Foundation. Circulytics. 2020. Available online: https://www.ellenmacarthurfoundation.org/resources/circulytics/resources (accessed on 25 February 2024).
17. Matthews, C.; Moran, F.; Jaiswal, A.K. A Review on European Union's Strategy for Plastics in a Circular Economy and its Impact on Food Safety. *J. Clean. Prod.* **2020**, *283*, 125263. [CrossRef]
18. Liu, W.; Zhu, Z.; Ye, S. A Framework towards Design for Circular Packaging (DfCP): Design Knowledge, Challenges and Opportunities. *Circ. Econ. Sustain.* **2023**, *3*, 2109–2125. [CrossRef]
19. Ellen MacArthur Foundation. New Plastics Economy. 2020. Available online: https://www.ellenmacarthurfoundation.org/our-work/activities/new-plastics-economy (accessed on 25 February 2024).
20. European Union. European Parliament and Council Directive 94/62/EC. *Off. J. Eur. Communities* **1994**, *1993*, 10–23.
21. Axelsson-Bacri, A.; Mikaela, N.; Tina, A.; Eric, L.N. *Recycling Food Packaging & Food Waste in Plastics Revolution*; EESC: Bruxelles, Belgium, 2020; ISBN 9789283048824.
22. Testa, F.; Di Iorio, V.; Cerri, J.; Pretner, G. Five shades of plastic in food: Which potentially circular packaging solutions are Italian consumers more sensitive to. *Resour. Conserv. Recycl.* **2021**, *173*, 105726. [CrossRef]
23. European Council. *Directive (Eu) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the Reduction of the Impact of Certain Plastic Products on the Environment*; European Council: Brussels, Belgium, 2019; Volume 2019, pp. 1–19. Available online: http://data.europa.eu/eli/dir/2019/904/oj (accessed on 25 February 2024).
24. Antonopoulos, I.; Faraca, G.; Tonini, D. Recycling of post-consumer plastic packaging waste in EU: Process efficiencies, material flows, and barriers. *Waste Manag.* **2021**, *126*, 694–705. [CrossRef] [PubMed]
25. Hahladakis, J.N.; Iacovidou, E. Closing the loop on plastic packaging materials: What is quality and how does it affect their circularity? *Sci. Total Environ.* **2018**, *630*, 1394–1400. [CrossRef] [PubMed]
26. Ding, Q.; Zhu, H. The Key to Solving Plastic Packaging Wastes: Design for Recycling and Recycling Technology. *Polymers* **2023**, *15*, 1485. [CrossRef]
27. Saidani, M.; Yannou, B.; Leroy, Y.; Cluzel, F.; Kendall, A. A taxonomy of circular economy indicators. *J. Clean. Prod.* **2019**, *207*, 542–559. [CrossRef]
28. Lonca, G.; Lesage, P.; Majeau-Bettez, G.; Bernard, S.; Margni, M. Assessing scaling effects of circular economy strategies: A case study on plastic bottle closed-loop recycling in the USA PET market. *Resour. Conserv. Recycl.* **2020**, *162*, 105013. [CrossRef]
29. De Pascale, A.; Arbolino, R.; Szopik-Depczyńska, K.; Limosani, M.; Ioppolo, G. A systematic review for measuring circular economy: The 61 indicators. *J. Clean. Prod.* **2021**, *281*, 124942. [CrossRef]
30. Kristensen, H.S.; Mosgaard, M.A. A review of micro level indicators for a circular economy–moving away from the three dimensions of sustainability? *J. Clean. Prod.* **2020**, *243*, 118531. [CrossRef]
31. Moraga, G.; Huysveld, S.; Mathieux, F.; Blengini, G.A.; Alaerts, L.; Van Acker, K.; de Meester, S.; Dewulf, J. Circular economy indicators: What do they measure? *Resour. Conserv. Recycl.* **2019**, *146*, 452–461. [CrossRef]
32. de Oliveira, C.T.; Dantas, T.E.T.; Soares, S.R. Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments. *Sustain. Prod. Consum.* **2021**, *26*, 455–468. [CrossRef]
33. Rossi, E.; Bertassini, A.C.; dos Santos Ferreira, C.; Neves do Amaral, W.A.; Ometto, A.R. Circular economy indicators for organizations considering sustainability and business models: Plastic, textile and electro-electronic cases. *J. Clean. Prod.* **2020**, *247*, 119137. [CrossRef]
34. Matos, J.; Martins, C.; Simões, C.L.; Simoes, R. Comparative analysis of micro level indicators for evaluating the progress towards a circular economy. *Sustain. Prod. Consum.* **2023**, *39*, 521–533. [CrossRef]
35. De Soares, C.T.M.; Ek, M.; Östmark, E.; Gällstedt, M.; Karlsson, S. Recycling of multi-material multilayer plastic packaging: Current trends and future scenarios. *Resour. Conserv. Recycl.* **2022**, *176*, 105905. [CrossRef]
36. Sánchez-Rivera, K.L.; del Carmen Munguía-López, A.; Zhou, P.; Cecon, V.S.; Yu, J.; Nelson, K.; Miller, D.; Grey, S.; Xu, Z.; Bar-Ziv, E.; et al. Recycling of a post-industrial printed multilayer plastic film containing polyurethane inks by solvent-targeted recovery and precipitation. *Resour. Conserv. Recycl.* **2023**, *197*, 107086. [CrossRef]
37. Ellen MacArthur Foundation. New Plastics Economy: Rethinking the Future of Plastics. 2016. Available online: https://www.ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics (accessed on 25 February 2024).
38. Moraga, G.; Huysveld, S.; De Meester, S.; Dewulf, J. Development of circularity indicators based on the in-use occupation of materials. *J. Clean. Prod.* **2021**, *279*, 123889. [CrossRef]
39. Hees, T.; Zhong, F.; Stürzel, M.; Mülhaupt, R. Tailoring Hydrocarbon Polymers and All-Hydrocarbon Composites for Circular Economy. *Macromol. Rapid Commun.* **2019**, *40*, 1800608. [CrossRef]

40. Hahladakis, J.N.; Iacovidou, E. An overview of the challenges and trade-offs in closing the loop of post-consumer plastic waste (PCPW): Focus on recycling. *J. Hazard. Mater.* **2019**, *380*, 120887. [CrossRef] [PubMed]
41. Gall, M.; Wiener, M.; de Oliveira, C.C.; Lang, R.W.; Hansen, E.G. Building a circular plastics economy with informal waste pickers: Recyclate quality, business model, and societal impacts. *Resour. Conserv. Recycl.* **2020**, *156*, 104685. [CrossRef]
42. Liang, W.Z.; Zhao, G.Y.; Hong, C.S. Performance assessment of circular economy for phosphorus chemical firms based on VIKOR-QUALIFLEX method. *J. Clean. Prod.* **2018**, *196*, 1365–1378. [CrossRef]
43. Saidani, M.; Kim, H.; Cluzel, F.; Leroy, Y.; Yannou, B. *Product Circularity Indicators: What Contributions in Designing for a Circular Economy?* Cambridge University Press: Cambridge, UK, 2020.
44. Rigamonti, L.; Mancini, E. Life cycle assessment and circularity indicators. *Int. J. Life Cycle Assess.* **2021**, *26*, 1937–1942. [CrossRef]
45. Ellen MacArthur Foundation. *Circularity Indicators: An Approach to Measuring Circularity—Non-Technical Case Studies*; Ellen MacArthur Foundation: Isle of Wight, UK, 2015; Volume 23, pp. 159–161.
46. Ellen MacArthur Foundation. Plastics and The Circular Economy. 2020. Available online: https://www.ellenmacarthurfoundation.org/explore/plastics-and-the-circular-economy (accessed on 3 November 2020).
47. Calisto Friant, M.; Vermeulen, W.J.V.; Salomone, R. Analysing European Union circular economy policies: Words versus actions. *Sustain. Prod. Consum.* **2020**, *27*, 337–353. [CrossRef]
48. Ellen MacArthur Foundation. Global Committment Progress Report. 2020. Available online: https://www.ellenmacarthurfoundation.org/news/global-commitment-2020-progress-report-published (accessed on 25 February 2024).
49. Plastics Europe; EPRO. *Plastics—The Facts 2018*; Plastics Europe: Brussels, Belgium, 2018; p. 38.
50. Albæk, J.K.; Shahbazi, S.; McAloone, T.C.; Pigosso, D.C.A. Circularity evaluation of alternative concepts during early product design and development. *Sustainability* **2020**, *12*, 9353. [CrossRef]
51. Kent, R. Design quality management. In *Quality Management in Plastics Processing*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 227–262. ISBN 9780081020821.
52. QualityInspection.org. The Design for X Approach: 12 Common Examples. 2021. Available online: https://qualityinspection.org/the-design-for-x-approach-12-common-examples/ (accessed on 2 September 2021).
53. Sassanelli, C.; Urbinati, A.; Rosa, P.; Chiaroni, D.; Terzi, S. Addressing circular economy through design for X approaches: A systematic literature review. *Comput. Ind.* **2020**, *120*, 103245. [CrossRef]
54. Dombrowski, U.; Schmidt, S.; Schmidtchen, K. Analysis and integration of design for X approaches in lean design as basis for a lifecycle optimized product design. *Procedia CIRP* **2014**, *15*, 385–390. [CrossRef]
55. Lee, S.G.; Lye, S.W. Design for manual packaging. *Int. J. Phys. Distrib. Logist. Manag.* **2003**, *33*, 163–189. [CrossRef]
56. Srinivas, H. *Guidelines Design for Evironment*; The Global Development Research Center: Pasig, Philippines, 2022. Available online: https://www.gdrc.org/uem/lca/guidelines.html (accessed on 25 February 2024).
57. Vaughan, R. *Design for Environment: Innovating to Compete*; Government of Canada: Ottawa, ON, Canada, 2009; Volume 39.
58. Postacchini, L.; Cicconi, P.; Ciarapica, F.E.; Germani, M.; Bevilacqua, M. A design method for improving assembly and environmental sustainability in packaging solutions: A case study in household appliances. *Int. J. Sustain. Eng.* **2021**, *14*, 574–589. [CrossRef]
59. Dalgleish, G.F.; Jared, G.E.M.; Swift, K.G. Design for assembly: Influencing the design process. *J. Eng. Des.* **2000**, *11*, 17–29. [CrossRef]
60. Fast Radius. *Design for Assembly (DFA)—What You Need to Know*; Fast Radius: Chicago, IL, USA, 2021. Available online: https://www.fastradius.com/resources/design-for-assembly-definition/ (accessed on 25 February 2024).
61. Mital, A.; Desai, A.; Subramanian, A.; Mital, A. *Designing for Assembly and Disassembly*; Wayken Rapid Manufacturing Limited: ShenZhen, China, 2014; ISBN 9780127999456.
62. Chai, T.C.; Zhang, X.; Li, H.Y.; Sekhar, V.N.; Hnin, W.Y.; Thew, M.L.; Navas, O.K.; Lau, J.; Murthy, R.; Balakumar, S.; et al. Impact of packaging design on reliability of large die Cu/low-κ (BD) interconnect. In Proceedings of the 2008 58th Electronic Components and Technology Conference, Lake Buena Vista, FL, USA, 27–30 May 2008; pp. 38–45. [CrossRef]
63. Swift, K.; Booker, J. *Manufacturing Process Selection Handbook*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2013; ISBN 9780080993577.
64. Formentini, G.; Boix Rodríguez, N.; Favi, C. Design for manufacturing and assembly methods in the product development process of mechanical products: A systematic literature review. *Int. J. Adv. Manuf. Technol.* **2022**, *120*, 4307–4334. [CrossRef]
65. East West Manufacturing. *What is Design for Manufacturing or DFM?* East West Manufacturing: Atlanta, GA, USA, 2020. Available online: https://news.ewmfg.com/blog/manufacturing/dfm-design-for-manufacturing (accessed on 25 February 2024).
66. Markforged. *The Importance of Design for Manufacturing*; Markforged: Waltham, MA, USA, 2022. Available online: https://markforged.com/resources/blog/importance-of-dfm (accessed on 25 February 2024).
67. Vezzoli, C.; Kohtala, C.; Srinivasan, A.; Diehl, J.C.; Fusakul, S.M.; Xin, L.; Sateesh, D. *Product-Service System Design for Sustainability*; Routledge: London, UK, 2014; ISBN 9781906093679.
68. Reliasoft. *Design for Reliability: Overview of the Process and Applicable Techniques*; Reliasoft: Tucson, AZ, USA, 2022. Available online: https://www.reliasoft.com/resources/resource-center/design-for-reliability-overview-of-the-process-and-applicable-techniques (accessed on 25 February 2024).
69. Ceschin, F.; Gaziulusoy, I. Evolution of design for sustainability: From product design to design for system innovations and transitions. *Des. Stud.* **2016**, *47*, 118–163. [CrossRef]

70. Kanwal, N.; Awan, U. *Role of Design Thinking and Biomimicry in Leveraging Sustainable Innovation*; LUT University: Lappeenranta, Finland, 2021; pp. 956–967. [CrossRef]
71. Mccall, T.G.; Walden, C.T. *Developing an Early Life Cycle Manufacturability Assessment for Conceptual Designs*; Mississippi State University: Starkville, MS, USA, 2022; Volume 1.
72. Shahin, A. Integration of FMEA and the Kano model. *Int. J. Qual. Reliab. Manag.* **2004**, *21*, 731–746. [CrossRef]
73. Uwera, J. Product Design and Its Impact on Consumer Purchase Decision. Case Study of TBL, Azam, Coca-Cola, MeTL and Tanga Fresh Milk in Tanzania. *Afr. J. Econ. Politics Soc. Stud.* **2022**, *1*, 129–153.
74. Bošnjaković, G.; Vladić, G. Research methodologies for assessing the ergonomics of packaging products-a review. In Proceedings of the 10th International Symposium on Graphic Engineering and Design, Novi Sad, Serbia, 12–14 November 2020; pp. 335–345. [CrossRef]
75. Amcor. *The Future of Packaging Is Here Sustinability Report 2023*; Amcor: Zürich, Switzerland, 2023.
76. Ellen MacArthur Foundation. *ANSYS Granta Circularity Indicators—An Approach to Measuring Circularity—Methodolofy*; Ellen MacArthur Foundation: Isle of Wight, UK, 2019; pp. 1–64.
77. Mohamed Sultan, A.A.; Lou, E.; Tarisai Mativenga, P. What should be recycled: An integrated model for product recycling desirability. *J. Clean. Prod.* **2017**, *154*, 51–60. [CrossRef]
78. Park, J.Y.; Chertow, M.R. Establishing and testing the "reuse potential" indicator for managing wastes as resources. *J. Environ. Manag.* **2014**, *137*, 45–53. [CrossRef]
79. IDEAL & CO Explore. Circularity Calculator. 2021. Available online: https://www.ideal-co.nl/tool.html#cc (accessed on 25 February 2024).
80. CradletoCradle. *Version 3.1 Cradle to Cradle Certified Product Standard*; CradletoCradle: Amsterdam, The Netherlands, 2016.
81. Di Maio, F.; Rem, P.C. A Robust Indicator for Promoting Circular Economy through Recycling. *J. Environ. Prot.* **2015**, *6*, 1095–1104. [CrossRef]
82. Linder, M.; Sarasini, S.; van Loon, P. A Metric for Quantifying Product-Level Circularity. *J. Ind. Ecol.* **2017**, *21*, 545–558. [CrossRef]
83. Franklin-Johnson, E.; Figge, F.; Canning, L. Resource duration as a managerial indicator for Circular Economy performance. *J. Clean. Prod.* **2016**, *133*, 589–598. [CrossRef]
84. Veleva, V.; Bodkin, G.; Todorova, S. The need for better measurement and employee engagement to advance a circular economy: Lessons from Biogen's "zero waste" journey. *J. Clean. Prod.* **2017**, *154*, 517–529. [CrossRef]
85. Di Maio, F.; Carlo, P.; Baldé, K.; Polder, M. Resources, Conservation and Recycling Measuring resource efficiency and circular economy: A market value approach. *Resour. Conserv. Recycl.* **2017**, *122*, 163–171. [CrossRef]
86. Bovea, M.D.; Pérez-Belis, V. Identifying design guidelines to meet the circular economy principles: A case study on electric and electronic equipment. *J. Environ. Manag.* **2018**, *228*, 483–494. [CrossRef] [PubMed]
87. Cayzer, S.; Griffiths, P.; Beghetto, V. Design of indicators for measuring product performance in the circular economy. *Int. J. Sustain. Eng.* **2017**, *10*, 289–298. [CrossRef]
88. Vogtlander, J.; Mestre, A.; Scheepens, A.; Wever, R. *Eco-Efficient Value Creation, Sustainable Design and Business Strategies*, 2nd ed.; Delft Academic Press: Delft, The Netherlands; VSSD: Kanpur, India, 2014; ISBN 9789065623683.
89. Figge, F.; Thorpe, A.S.; Givry, P.; Canning, L.; Franklin-Johnson, E. Longevity and Circularity as Indicators of Eco-Efficient Resource Use in the Circular Economy. *Ecol. Econ.* **2018**, *150*, 297–306. [CrossRef]
90. Lee, H.M.; Lu, W.F.; Song, B. A framework for assessing product End-Of-Life performance: Reviewing the state of the art and proposing an innovative approach using an End-of-Life Index. *J. Clean. Prod.* **2014**, *66*, 355–371. [CrossRef]
91. Favi, C.; Germani, M.; Luzi, A.; Mandolini, M. A design for EoL approach and metrics to favour closed-loop scenarios for products A design for EoL approach and metrics to favour closed-loop scenarios for products. *Int. J. Sustain. Eng.* **2017**, *10*, 136–146. [CrossRef]
92. Lacovidou, E.; Velenturf, A.P.M.; Purnell, P. Science of the Total Environment Quality of resources: A typology for supporting transitions towards resource ef fi ciency using the single-use plastic bottle as an example. *Sci. Total Environ.* **2019**, *647*, 441–448. [CrossRef] [PubMed]
93. Mesa, J.; Esparragoza, I.; Maury, H. Developing a set of sustainability indicators for product families based on the circular economy model. *J. Clean. Prod.* **2018**, *196*, 1429–1442. [CrossRef]
94. Cong, L.; Zhao, F.; Sutherland, J.W. Product Redesign for Improved Value Recovery via Disassembly Bottleneck Identification and Removal. *Procedia CIRP* **2017**, *61*, 81–86. [CrossRef]
95. Zwolinski, P.; Lopez-Ontiveros, M.A.; Brissaud, D. Integrated design of remanufacturable products based on product profiles. *J. Clean. Prod.* **2006**, *14*, 1333–1345. [CrossRef]
96. Alamerew, Y.A.; Brissaud, D. Evaluation of Remanufacturing for Product Recovery: Multi-criteria Decision Tool for End-of-Life Selection Strategy. In Proceedings of the 3rd International Conference on Remanufacturing, Linköping, Sweden, 23–26 October 2017.
97. Van Schaik, A.; Reuter, M.A. Recycling indices visualizing the performance of the circular economy. *World Metall.–ERZMETALL* **2016**, *69*, 201–216.
98. Ameli, M.; Mansour, S.; Ahmadi-javid, A. Resources, Conservation & Recycling A simulation-optimization model for sustainable product design and efficient end-of-life management based on individual producer responsibility. *Resour. Conserv. Recycl.* **2019**, *140*, 246–258. [CrossRef]

99. Madruga, P.; Rodrigues, H. *Indicadores de Economia Circular: Um Contributo para o Sistema Estatístico Nacional*; Lipor: Maia, Portugal, 2020.
100. Almeida, C.; Berardi, P.; Chaves, M.C. *Estudo Comparativo dos Indicadores Existentes de Economia Circular com Perspetivas à Criação de uma Ferramenta de Monitorização Aplicada à Realidade Nacional Portuguesa*; Universidade do Porto: Porto, Portugal, 2020.