sustainability

Review

Defining Circular Economy Principles for Biobased Products

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Abstract: To support progress towards the transition to a circular economy, the ability to measure circularity is essential. The consideration of the role biobased products can play in this transition is however still largely lacking in the current development of circularity monitoring approaches. The first step in coming to a suitable monitoring framework for biobased products is to define circular economy principles. In this paper, specific characteristics of biobased products were considered in defining six circular economy principles for biobased products: (1). Reduce reliance on fossil resources, (2). Use resources efficiently, (3). Valorize waste and residues, (4). Regenerate, (5). Recirculate and (6). Extend the high-quality use of biomass. In order to evaluate the circularity performance of biobased products with respect to these principles, what needs to be measured was defined considering both intrinsic circularity and impact of this circularity. The intrinsic indicators provide a measure of success in implementation of these circularity principles, and the latter impacts of circularity, i.e., impact of closing the loops on accumulation of hazardous substances and impact of circularity on sustainability (environmental, economic and social). Yet, to unlock the potential of a sustainable circular bioeconomy, strong accompanying measures are required.

Keywords: circular economy; bioeconomy; biobased products; circularity metrics; indicators; sustainability

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1. Introduction

Currently, about 90% of global biodiversity and water stress impacts and about half of global climate change emissions are caused by resource extraction and processing [1]. It is therefore no surprise that in the European policy ambitions of reaching climate change mitigation and conservation of our natural resources, there is an urgency of taking measures to increase resource efficiency, decouple economic growth from resource use and stimulate a more sustainable production and consumption system. These measures all come together in the concept of circularity, which has as a main aim to reduce resource consumption and emissions to the environment by closing the loop of materials with linkages between different industries [2], and designing waste out of the system [3].

The instrument of circularity was embraced in EU policy in 2013 through the statement in the seventh Environment Action Plan "Our prosperity and healthy environment stem from an innovative, circular economy where nothing is wasted and where natural resources are managed sustainably, and biodiversity is protected, valued and restored in ways that enhance our society's resilience" [4]. Soon after, the European Commission (EC) launched the Circular Economy Package [5], which created the basis for the current EC ambitions for reaching climate neutrality and wider sustainability through further transition to a circular economy. This circularity was also coupled with a transition to a bioeconomy [6]. The concept of a bioeconomy was put forward by the EC in 2012 [7], and the 2018 update of the Bioeconomy Strategy of the EC indicated that the "European Bioeconomy needs to have sustainability and circularity at its heart" [8].

The 2018 update of the Bioeconomy Strategy, the Green Deal [9], and the New Circular Economy Action plan [10], have all helped to clarify further how and with what instruments the EC is planning to bring about the transition to further circularity. EC thereby set up a monitoring framework on the circular economy with a set of indicators on the macro scale (EU, or Member State level) [11]. Recently, the term circular bioeconomy has been introduced to intertwine the bioeconomy and circular economy concepts [12–15], and also appeared in EC communication [16].

Different circular economy strategies and principles have been proposed by governments, industry, non-governmental organizations and academics [3,17–19]. As included in the definition of the circular economy, proposed by Kirchherr et al., the circular economy "operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond)" [20]. The focus of this paper is on the micro level and specifically on biobased products, which are products that are wholly or partly derived from biomass [21].

The "butterfly" diagram of Ellen MacArthur Foundation distinguishing between technical and biological cycles could be quite misleading in this respect, as biomass use seems to be existing only in the biological cycle [22], but in reality biomass also enters in the technical cycle and is used in the production of chemicals, plastics and materials. Following circular economy principles, biobased products can be kept in the technical cycle through reuse and recycling, optimizing the time spent in each cycle and the number of consecutive cycles. The product can cascade through multiple uses and achieve substantial reduction in virgin material inflow by each consecutive application. Some of these biobased products can contribute to organic recycling through composting or in-situ biodegradation, which contributes to regeneration of natural systems (in the biological cycle). Therefore, it is relevant to capture these characteristics in considering how circularity should be defined and monitored for biobased products. Such concrete research on circular economy monitoring including these characteristics is currently lacking.

Given the combined central roles circularity and the bioeconomy play in the policy ambitions of the EU and EU Member States for reaching climate neutrality and wider sustainability, the increase in biomass as a renewable resource in the economy should also go together with a more sustainable and circular use of biomass. A suitable framework based on a comprehensive list of circular economy principles is required to be able to measure and monitor this. Accordingly, the aim of this study is to: (1) define circular economy principles for biobased products by complementing existing principles with specific considerations relevant for biobased systems (e.g., cascading use of biomass, regeneration of natural systems), and (2) identify what needs to be measured for monitoring circularity of biobased products considering measure of intrinsic circularity as well as the impacts of circularity.

2. Materials and Methods

The method applied in this study to define circular economy (CE) principles and what needs to be measured for monitoring circularity for biobased products consisted of three steps: (1) Literature search on general CE strategies, (2) Method for identifying core characteristics of the circular bioeconomy, and (3) Identifying what needs to be measured for monitoring circularity of biobased products. In the first two steps, a systematic literature review was conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [23], aiming at both peer-reviewed articles and grey literature (i.e., reports, commercial publications, etc.).

2.1. Literature Search on General Circular Economy Principles and Strategies

Seeing that there is no one agreed definition of CE and its principles, the first step was reviewing the general CE principles, strategies or requirements defined by different stakeholders in scientific and grey literature. As global thought leader for the transition to a circular economy, principles defined by Ellen MacArthur Foundation [3] were taken into consideration. In the context of CE principles, also most often R-frameworks and hierarchies have been defined, including the most prominent 3Rs (reduce-reuse-recycle) [24] and the 4R framework with the inclusion of Recover [25]. The R frameworks addressed in academic literature were recently extensively reviewed by Reike et al. [19]. This study was used as input and complemented with the report of Netherlands Environmental Assessment Agency from grey literature in providing an overview of the more nuanced R hierarchies [18].

Additionally, several scientific articles included CE principles in categorizing and evaluating existing metrics at product level. To identify these, a systematic review was conducted where the Scopus database was used for material collection. An advanced search was carried out with the keywords "circular economy" and "principle, strategy or requirement" using Boolean operators (Search string: ABS ("circular economy") AND ABS (principle OR strategy OR requirement) AND ABS (micro OR product) AND ABS (indicator OR index OR metric) AND LANGUAGE (English)) AND PUBYEAR > 2009 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re") on 1 April 2022). Filters were applied to the Scopus database on document type and language to filter peer-reviewed papers (article and review) published in scientific journals in English. This search resulted in 134 papers. The search was followed by a screening process, performed by reading the title and abstract of every document against the inclusion criteria, which were that study addresses circular economy principles, strategies or requirements. After this filter, 16 articles were pre-selected based on relevance. The next step was going through the full text of these pre-selected papers to identify the ones that had a specific listing of the set of CE principles that they considered. This resulted in 9 articles, which were included in this review [26–34]. The literature review process is summarized in Figure 1.

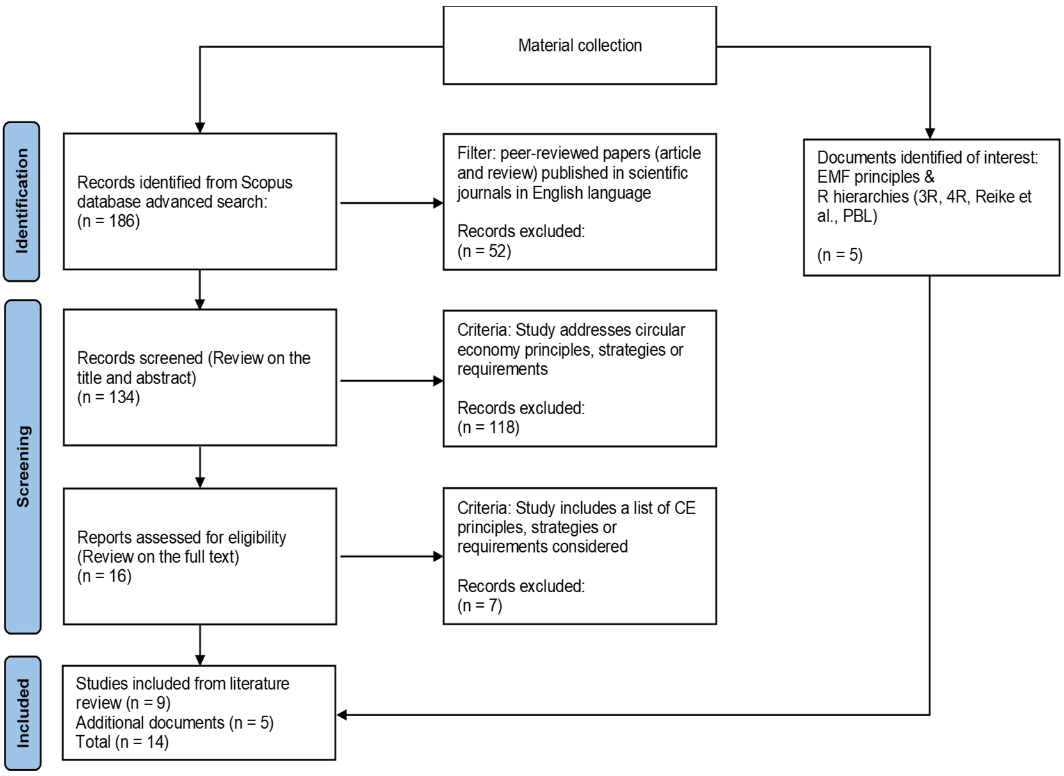

Figure 1. Review process on general CE principles following the PRISMA guidelines [19].

2.2. *Identifying Core Characteristics of Circular Bioeconomy and Defining CE Principles for Biobased Products*

In the second step, specific characteristics of biobased systems relevant for the circular economy were identified through a review of scientific and grey literature on this field. An internet search was carried out using the key words "circular bioeconomy", "circular biobased economy", or combination of "circular economy" with "bioeconomy" or "bio-based economy". This search yielded 5 key reports from grey literature for review [6,12–14,35]. Additionally, the same keywords were used in another Scopus advanced search (Search string: TITLE ("circular bioeconomy" OR "circular bio-based economy" OR "circular bio-economy" OR "circular bio-based") AND LANGUAGE (English)) AND PUBYEAR > 2009 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re") on 1 April 2022) to find papers on this topic in scientific literature. Filters were applied to the Scopus database on document type and language to filter peer-reviewed papers (article and review) published in scientific journals in English. This search yielded 190 documents, which was followed by a screening process performed by reading the title and abstract of every document to filter against the inclusion criteria of studies that specifically address circular bioeconomy characteristics or principles. After this filter, 10 articles were pre-selected based on relevance. The next step was going through the full text of these pre-selected papers to identify the ones that had a specific listing of circular bioeconomy criteria, principles or characteristics. This resulted in 6 articles [15,36–40]. The findings and insights collected from this literature review of 11 documents (5 from grey literature, 6 from scientific literature) were complemented with authors' own expertise on this topic to define CE principles for biobased products, building upon existing general CE principles (reviewed in step one). The literature review process is summarized in Figure 2.

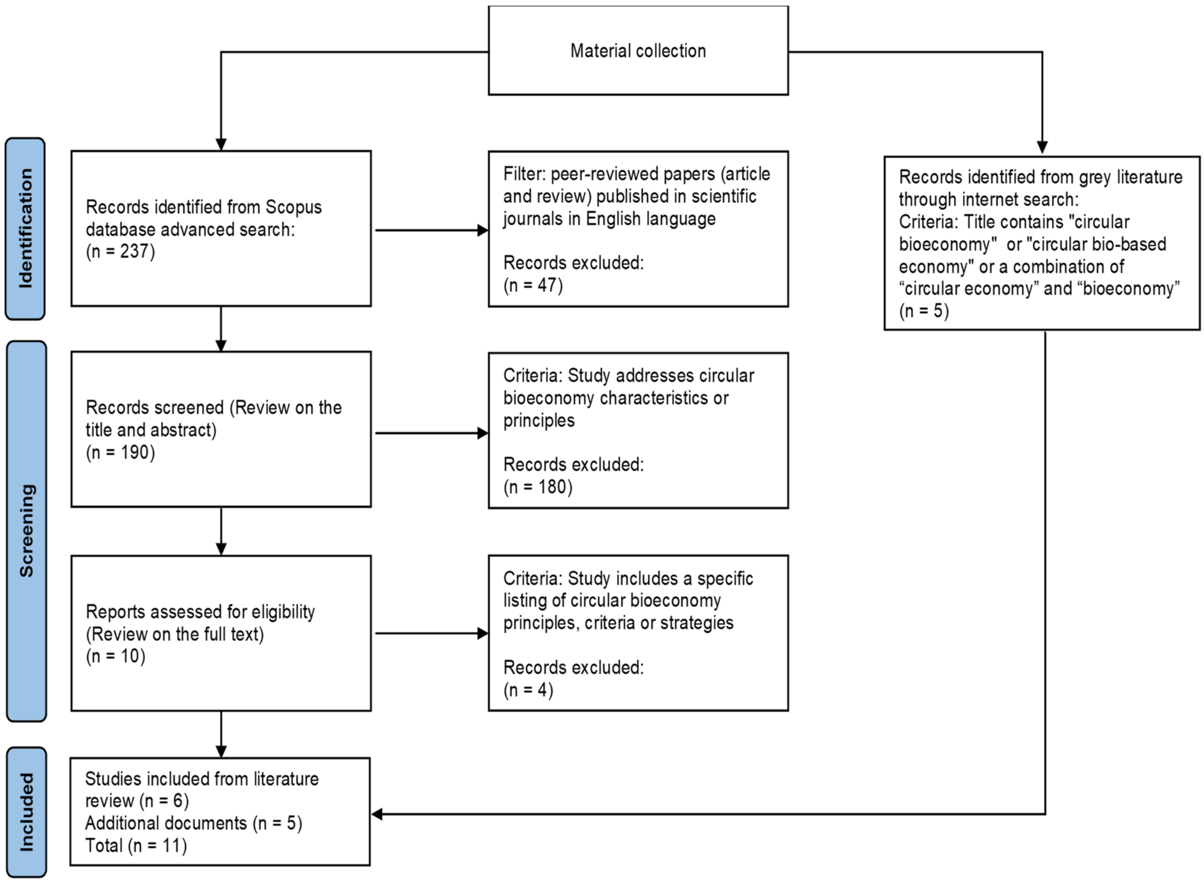

Figure 2. Review process on specific circular bioeconomy characteristics following the PRISMA guidelines.

2.3. Identifying What Needs to Be Measured for Monitoring Circularity of Biobased Products

Step three concerns identifying what needs to be measured for monitoring circularity of biobased products. This was determined considering both intrinsic circularity (that measures the inherent circularity) and its impacts (depicting the burdens or benefits of CE loops). This categorization was also applied by Saidani et al. 2019 regarding circularity performance, i.e., indicators that measure the inherent circularity and indicators that depict the consequences of CE loops [41]. Furthermore, both Potting et al. (2017) [18] and EEA (2016) [17] considered that assessing the circularity performance should address both the progress of the process of the transition to CE and its effects.

Accordingly, the first category refers to intrinsic indicators that should provide a measure for the CE principles defined for biobased products (in step 2). The second category refers to indicators that should provide a measure of the impacts of circularity. For this, impact of closing the loops on accumulation of hazardous substances was considered as well as the impact of circularity on sustainability, considering all three dimensions (environmental, economic and social).

3. Results

3.1. Circular Economy Principles and Strategies—What to Measure?

Review of scientific and grey literature revealed that different circular economy principles and strategies have been proposed. The set of requirements provided in each source are presented in Table 1.

Table 1. Collation of circular economy principles/strategies/requirements.

Source	Circular Economy Principles/Strategies/Requirements
Ellen Mac Arthur Foundation [3]	1. Design out waste and pollution 2. Keep products and materials in use 3. Regenerate natural systems
Boyer et al. (2021) [29]	1. Material circulation 2. Utilization 3. Endurance
3R Framework [24]	1. Reduce 2. Reuse 3. Recycle
4R [25]	1. Reduce 2. Reuse 3. Recycle 4. Recover
Saidani et al. (2017) [30]	1. Maintain/Prolong 2. Reuse/Redistribute 3. Refurbish/Remanufacture 4. Recycle
Alamerew et al. (2020) [31]	1. Reuse 2. Repair 3. Refurbish 4. Recondition 5. Remanufacture 6. Repurpose 7. Cannibalization (recover parts) 8. Recycle
PBL [18]	1. Refuse 2. Rethink 3. Reduce 4. Reuse 5. Repair 6. Refurbish 7. Remanufacture 8. Repurpose 9. Recycle 10. Recover

Table 1. *Cont.*

Source	Circular Economy Principles/Strategies/Requirements
Reike et al. (2018) [19]	1. Refuse 2. Reduce 3. Reuse 4. Repair 5. Refurbish 6. Remanufacture 7. Repurpose 8. Recycle 9. Recover 10. Re-mine
Ortiz-de-Montellano and van der Meer (2022) [34]	1. Redesign 2. Reuse 3. Resell 4. Remanufacture/refurbish 5. Recycle 6. Recover 7. Recirculate
Kristensen and Mosgaard (2020) [32]	1. Recycling 2. Remanufacturing 3. Reuse 4. Resource-efficiency 5. Disassembly 6. Lifetime extension 7. Waste management 8. End-of-life management
Jerome et al. (2022) [33]	1. Reducing losses in production 2. Changing material composition (recycled, renewable content) 3. Using more of technical lifetime (include reuse and remanufacture) 4. Material recycling 5. Energy recovery)
Moraga et al. (2019) [28]	1. Function e.g., refuse, rethink, reduce 2. Product e.g., reuse, refurbish, remanufacture 3. Component e.g., reuse, repurpose 4. Material e.g., recycle 5. Embodied energy e.g., recover 6. Measure the linear economy as the reference scenario)
Elia et al. (2017) [26]	1. Reducing input and use of natural resources 2. Reducing emissions levels 3. Reducing valuable material losses, wastes 4. Increasing the share of renewable and recyclable resources 5. Increasing the value durability of products)
Corona et al. (2019) [27]	1. Reducing input of resources, especially scarce ones 2. Reducing emission levels (pollutants and GHG emissions) 3. Reducing material losses/waste 4. Increasing input of renewable and recycled resources 5. Maximizing the utility and durability of products 6. Creating local jobs at all skill level 7. Value added creation and distribution 8. Increase social wellbeing)

Several ladders, or R-frameworks, position the CE strategies. All R frameworks have a hierarchy as they are ordered from high priority towards low priority in the order of high to low level of circularity. The R framework was developed at first as a 3R framework (Reduce, Reuse, Recycle) [24]. It evolved into a 4R framework with the inclusion of Recover as the fourth R, in accordance with the European Union's Waste Framework Directive considering incineration of materials with energy recovery [25]. While these have been well accepted and applied, there has recently been emphasis on more nuanced hierarchies reaching up to 10 Rs [19]. Saidani et al. (2017) ranked the different circularity loops from the most inner-loop to the most outer-loop according to the Ellen MacArthur Foundation's circular economy model grouped into four categories (Maintain/Prolong, Reuse/Redistribute, Refurbish/Remanufacture, Recycle) [22]. PBL's circularity ladder includes 10 Rs [18]. They are grouped into three categories of "smarter product use and manufacture" (R0–R2), "extend lifespan of product and its parts" (R3–R7) and "useful application of materials" (R8–R9). Therefore, the focus is on functionality first, then on preserving products and their parts and after that on recycling materials and energy recovery. Review of Reike et al. (2018) of R frameworks revealed not only varying numbers of Rs used in different studies (ranging from 3 to 10 Rs) as well as varying conceptualizations of each principle [19]. Accordingly, they synthesized the most common perspectives into a single systemic typology composed of 10 Rs, which they refer to as value retention options. It has almost the same list of principles as PBL (there is no rethink at level 2; instead, there is a re-mine at level 10), similarly distinguishing between short, medium and long loops. The term value retention was recently also used by Ortiz-de-Montellano and van der Meer (2022) where they considered eight value retention stages with Redesign placed at first [34].

CE requirements were included in several review papers that evaluated existing circularity metrics. Moraga et al. (2019) [28] defined six CE strategies inspired by PBL's circularity ladder [18] to classify indicators. The first five strategies acknowledge preservation (of function, product, product's components, material and embodied energy), and the last strategy considers the measurement of the linear economy as a reference scenario. Elia et al. (2017) [26] considered five requirements that were deduced from an European Environmental Agency report [17]. All the circular economy strategies aim to bring about reduction in resource use, which is captured in the first requirement. The third requirement links to recycling materials and fifth requirement links to the lifespan extension strategies of products (R3-R7 of PBL). The second and fourth are not explicitly covered in the above strategies. The second requirement considers the effect of the circular economy on environment where it is expected that increasing the circularity of a product will decrease emissions as well. The fourth requirement considers the substitution of virgin resources with renewable and recycled resources. This is also included in the CE strategies of Jerome et al. (2022) as changing material composition looking either at recycled or renewable content [33].

Corona et al. (2019) [27] came up with a similar list of CE requirements for reviewing existing metrics including the five requirements of Elia et al. (2017) [26]. Additionally, they considered the effect of the circular economy on economic prosperity and social equity. Accordingly, they included three extra requirements concerning creating jobs, value added creation and increase of social wellbeing.

3.2. Biobased Products: Circular Economy Principles and Measurement Needs

In defining circular economy principles, additional considerations are needed looking at the role of the bioeconomy in the circular economy. The European Bioeconomy Alliance defines bioeconomy as "the biological motor of a future circular economy, which is based on optimal use of resources and the production of primary raw materials from renewably sourced feedstock" [35]. Navare et al. (2021) specified characteristics of biological cycles in the context of CE with focus on aspects that are not addressed by existing monitoring systems [36]. These are renewability, potential for cascading use of material, and closing the nutrient cycle. Additionally, Kardung et al. (2021) pointed out that two essential concepts that should be captured in monitoring the biobased economy are biorefineries and cascading use of biomass [37]. EEA sees cascading biomass use and recycling while preserving natural capital as core of a sustainable and circular bioeconomy [6]. Bos and Broeze (2020) identified four priorities for biobased product systems: 1. Maintaining soil health, with responsible exploitation of crop residues for biobased applications; 2. Circular nutrient management; 3. Replacement of fossil sources by renewables, valorization of side streams and 4. Increasing multifunctional use and recycling of biobased materials [38]. Additionally, Muscat et al. (2021) presented five ecological principles to guide biomass use: Safeguarding and regenerating the health of our (agro)ecosystems; Avoiding non-essential products; Prioritizing biomass streams for basic human needs (considering also cascading use); Recycling nutrients and carbon from by-products into the bio-based system; and Minimizing overall energy use and using renewable energy [39].

Some authors looked at the intersection of the bioeconomy and circular economy concepts. Brandão et al. (2021) defined three key interfaces between the bioeconomy and circular economy: Utilization of biomass as a resource including by-products, residues and waste, Cascading use of biomass; and Minimize use of fossil fuels (creating a more sustainable and resource-efficient world) [40]. Additionally, they highlighted resource-efficient valorization of biomass with biorefineries as a key part of a circular bioeconomy. Stegmann et al. (2020) identified key elements of a circular bioeconomy based on a literature review, which include resource-efficiency; biorefinery; use of wastes and residues as resource; maintaining the value of products, materials and resources for as long as possible; cascading use of biomass; and waste management (e.g., reuse, recycling) [15]. In another study, cascading use, utilization of waste streams, resource-efficient value chains, reuse, recycling and organic and nutrient cycling were defined as common elements of the bioeconomy and circular economy [12].

It is seen from this review that some key aspects are repeated specific to use of biomass towards a circular bioeconomy. First is the role of biobased products in reducing reliance on fossil resources. Biomass provides renewable carbon to the economy and can replace fossil carbon [13], thereby any virgin feedstock input demand in the circular economy can be supplied in a renewable way. The second key aspect is using resources efficiently where the role of biorefining is highlighted. Biorefining allows processing of biomass into a spectrum of products and is seen as a major enabling strategy of the circular economy [42]. Then, the third key aspect is the valorization of residues and wastes. A biobased economy allows utilization of biological residues and wastes from variety of sources and can bring these products into the circular economy [14]. As was also included in the CE principles defined by Ellen Mac Arthur Foundation, regeneration of natural systems is a key consideration, which is about closing the carbon and nutrient cycles in the biosphere [43]. This fourth key aspect of regeneration incorporates returning of nutrients and organic matter from residual and waste streams back to soil. Recycling and lifetime extension strategies are equally valid for biobased products, therefore the fifth and sixth key aspects are "recirculate" and "extend the high-quality use of biomass". One integral consideration here is the possibility of cascading use of biomass, defined as the strategy to use "the biomass as long, often and efficiently as possible for materials and only to recover energy from them at the end of the product life cycle" [44].

Accordingly, six circular economy principles for biobased products were derived as included in Table 2 and illustrated in Figure 3. The description of each principle is provided below.

Table 2. Circular economy principles and what needs to be measured for monitoring circularity of biobased products.

Circular Economy Principles:	What Needs to Be Measured:
1. Reduce reliance on fossil resources 2. Use resources efficiently (including biorefining) 3. Valorize waste and residues 4. Regenerate 5. Recirculate 6. Extend the high-quality use of biomass (including cascading use)	1. Share of renewable resources 2. Resource use efficiency (include use of residues) 3. Degree of regeneration 4. Degree of recirculation 5. Utility (include cascading use) 6. Risk of accumulation of hazardous substances 7. Effect on environmental protection 8. Effect on economic viability (e.g., costs, value added) 9. Effect on social equity (e.g., jobs creation, wellbeing)

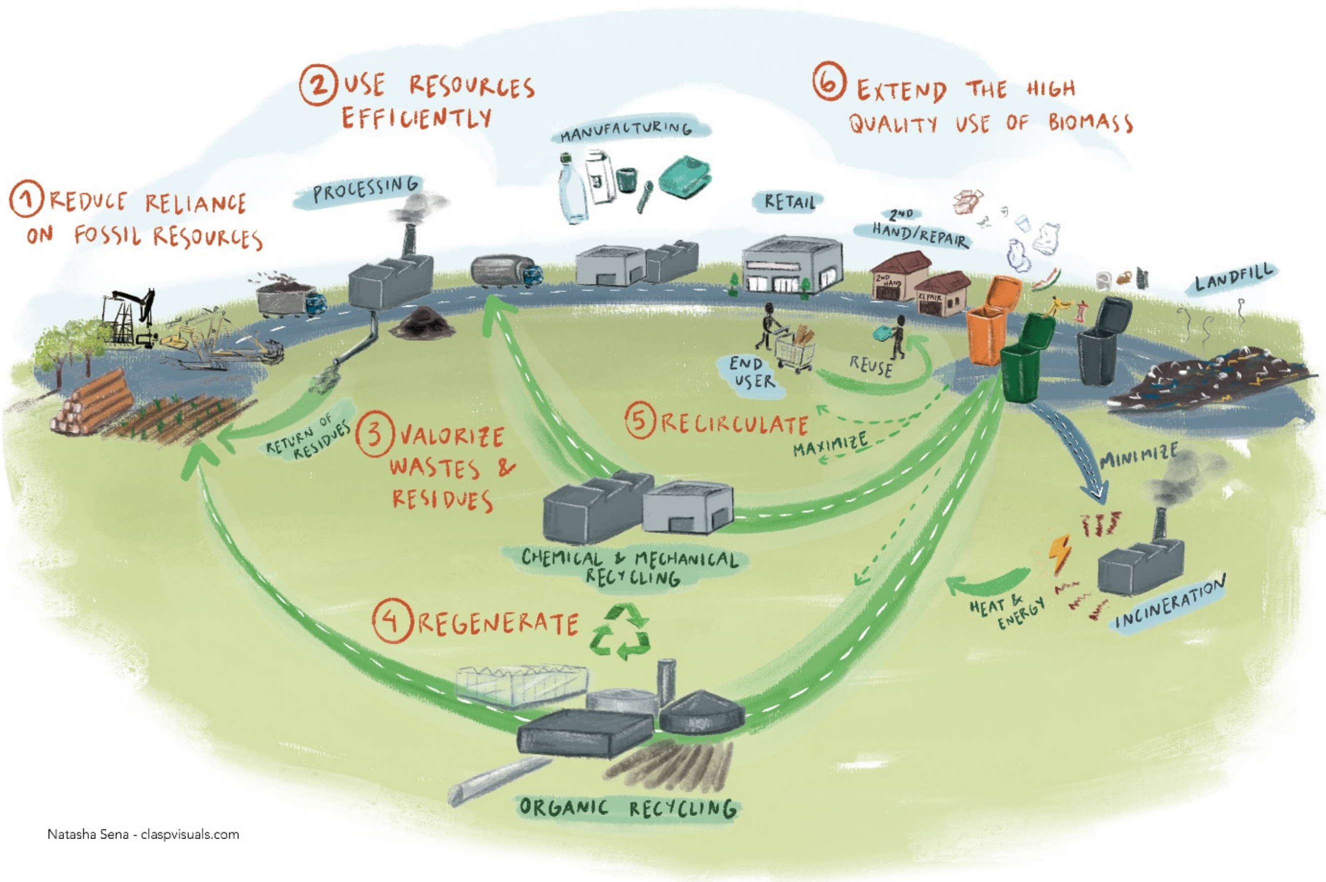

Figure 3. Illustration of a biobased product system and the defined circular economy principles (source: Authors' own elaboration visualized by Natasha Sena).

3.2.1. Reduce Reliance on Fossil Resources

Transitioning from fossil resources to renewable resources such as biomass is an important aspect of the circular economy. The biobased economy covers a wide variety of products and industrial sectors, such as plastics, chemicals, pharmaceuticals, packaging, construction, textiles, and bioenergy [13]. Energy and transport fuels from fossil resources can largely be replaced by renewable energy and hydrogen, which are non-carbon-based solutions. In order to phase out the use of fossil feedstock in other sectors, there is requirement for renewable carbon [45]. Here, use of biomass is indispensable to meet the carbon demand of materials and chemicals that cannot be supplied with renewable energy (solar, wind, hydro and geothermal). This integral role of biogenic carbon for the circular economy was realized and recently coined with the term "biobased circular carbon economy". For heavy transport, shipping and aviation fuels, biomass use is currently needed until other sustainable solutions become available [46]. As defined in the Dutch government wide Circular Economy program [47], "in case new raw materials are necessary, fossil-based, critical and non-sustainably produced raw materials must be replaced by sustainably produced, renewable and generally available raw materials." As the decarbonization of the energy sector advances, it is considered that bioenergy and biofuels for light road transport will be phased out in the future and the released biomass can be used to supply the demand of the chemicals and materials sector [46]. Biomass will therefore be essential in meeting carbon-based non-food demands in industry and reduce dependence on fossil resources. The only other (virgin) alternative to fossil-based resources is through carbon capture and utilization which is still at an early stage of development [48].

3.2.2. Use Resources Efficiently (Including Biorefining)

As the demand for biomass increases, not only for food and feed but also for fuel, chemicals and materials, increasing competition for biomass, land and other natural resources will occur [49]. Although trade-offs exist, there is a possibility to have resource-efficient valorization of biomass with multi-output production where different products are attained from different components. Biomass components are fibers (cellulose, hemicellulose and lignin), carbohydrates (starch, sugars), oil, protein, minerals and high-added-value ingredients (such as pigments, aromatics). The composition of these components largely varies in different biomass sources. For the purpose of utilizing biomass in the bioeconomy, it is important to link these biomass components with the suitable applications [50].

Multi-output production is key for resource efficiency that is achieved through biorefining of biomass into a spectrum of biobased products (food, feed, chemicals, materials) and bioenergy (biofuels, power and/or heat) [51]. This considers an increased valorization of biomass components through the connection of additional processes and new technologies in an integrated way for an expanded range of products. This allows reducing waste formation as the side and residual streams arising are turned into products for various market sectors. An example is the Roquette Lestrem biorefinery, which was a simple starch mill that was gradually developed, and the product spectrum increased to native and modified starches, proteins, polyols, organic acids and specialty chemicals [52]. There is also increased development of biorefinery concepts that utilize resources that are not food crops (i.e., sugar, starch and oil crops). These include biorefineries that use lignocellulosic biomass (wood, forestry and agricultural residues, energy crops), aquatic biomass, natural fibers (e.g., hemp) and municipal solid waste [52].

Currently, biorefineries are energy-driven, where the main products are biofuels, power and heat, owing to the existing biofuel-related policy targets supporting the use of biomass for bioenergy production [53]. No such directive exists yet for the use of biomass for chemicals/materials. However, the principles of the circular economy favor the use as a material over energy use. Accordingly, it is desirable that future biorefineries transition towards a more product-driven (materials and chemicals) approach [46]. The transition from a fuel to a material focus could, for example, be achieved in existing biorefineries by diverting bioethanol from fuel use towards chemical use, and the use of sugars to produce other chemicals through chemical conversion or fermentation. Similarly, also use of fatty acid methyl esters for production of fatty alcohols, for example in the production of surfactants instead of use as biodiesel fuel. This shift will also reduce demand for additional biomass to be used in the production of biobased products.

A potential to alleviate pressure on fertile soil and competition with food/feed production is to grow biomass on polluted or contaminated lands for non-food applications. This ideally also improves the quality of contaminated soil over the long term [54]. However, some non-food applications may still be problematic as the resulting products can contain high pollution levels, which can still end up in the environment or remain a threat to humans [55]. For example, if biomass polluted with high levels of heavy metal is converted into a biofuel, this requires specific pre-treatment to render the contaminants and prevent them entering into the environment during the conversion [56].

3.2.3. Valorize Wastes and Residues

The production, conversion and use of biomass results in various residues and wastes. While resource use efficiency (second principle) requires minimizing waste, it cannot be fully eliminated. Thereby the possibility to valorize the residues and waste is important for the circular economy [14]. Distinction is made between primary, secondary, and tertiary residual flows (see Figure 4). The primary resides are parts of plants that are left on the field or in the forest after harvesting of the biomass. The secondary residues are all forms of biomass that arise from processing of the biomass in industry (such as agro-food, woodworking) where the production of the residue was not the purpose of the process. There are also tertiary residues or wastes that have already had a use (post-consumer) that consist partly or fully of biological material such as organic household waste, food waste, sewage sludge [57]. More effective use of biogenic waste and residues for feed and as feedstock for the chemical, material and energy applications (see Figure 5, 3rd cycle) can reduce the need for additional primary biomass production for these applications.

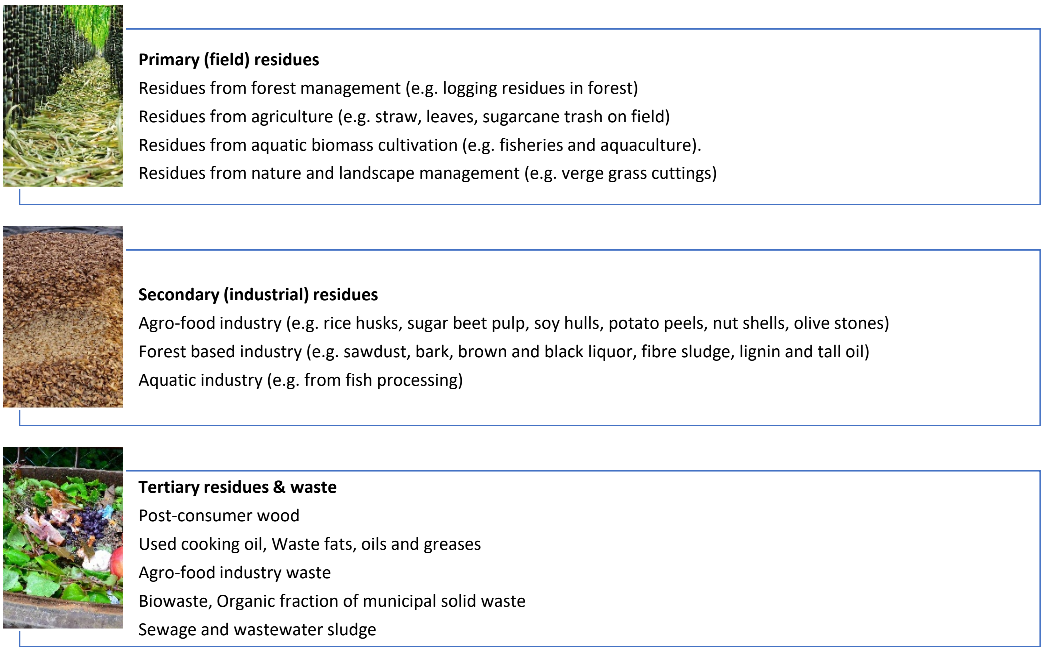

Figure 4. Biomass residues and wastes (source: Authors' own elaboration).

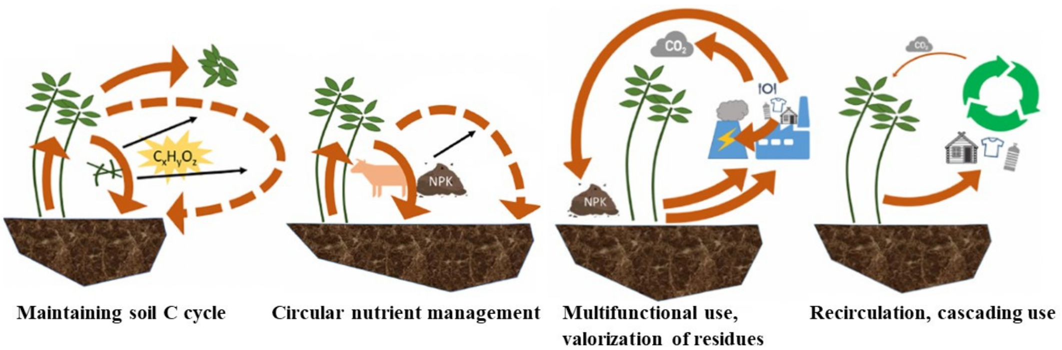

Figure 5. The cycles to optimize and extend to improve the circularity of biomass use in bioeconomy (source: Bos and Broeze (2020) [38]).

This categorization of residues is relevant because different sustainability considerations are relevant for the different types as well as in which applications they can be used for [58]. For primary residues, it is important to consider the soil quality and the sustainable harvest levels of the residues to maintain soil health and biodiversity. For tertiary residues, most have the status of waste in a legal sense and are subject to the EU Waste Framework Directive where the waste hierarchy must be followed [14] Therefore, it favors the food, feed, material and chemical applications over energy recovery. The tertiary residues and wastes also include biowaste that can be composted and serve as a valuable source of organic matter to return to soil (related to the fourth principle, regenerate). One strategy is to prioritize the use of biomass for human consumption and recycling any by-products for use in the economy [49]. Applications of food waste in the bioeconomy are increasing very strongly [14,59], such as the conversion of bread waste to succinic or lactic acid. Food processing residues can also be an interesting source of oil, which can have high value applications, such as avocado oil from rejected fruits, fish oil from lean fish and fish processing residues [60]. These and other examples are catalogued in the Power4Bio project [61].

3.2.4. Regenerate (Maintain Carbon and Nutrient Cycles)

It is required to ensure that the biomass production system remains healthy. As the Ellen MacArthur foundation prescribes, we need to "preserve and enhance natural capital by controlling finite stocks and balancing renewable resources flows" [43]. This concerns maintaining the essential soil carbon and nutrient cycles (see Figure 5, first two cycles). The soil carbon cycle concerns leaving enough crop residues in the field to maintain the soil organic matter content and valorize the excess in the biobased economy [62]. The soil carbon cycle also concerns converting organic wastes to compost and returning to soil. This can allow additional crop residues to become available for the bioeconomy. The nutrient cycle considers effective nutrient management to reduce losses and minimize dependence on artificial fertilizers by bringing manure to the required farmlands as well as regenerative agricultural practices such as crop rotations and use of cover crops [38,43]. Application of digestate (by-product from anaerobic digestion) as a fertilizer is another consideration here. Mineral-rich biomass sources such as manure, organic waste and wastewater sludge can go into anaerobic digestion, which generates biogas and digestate [63]. Biogas can be applied directly for energy use, or it can be upgraded to biomethane and used for energy or transport fuel thereafter. The by-product digestate contains minerals and organic material that can be used as a fertilizer returning carbon and nutrients to soil [50]. This enables the replacement of industrially produced mineral fertilizers [64].

For nutrient management, bringing manure or nutrient-rich residual streams in appropriate places and amounts is needed [6]. It is often seen that supply and uptake are not balanced, where both the surplus and deficit of nutrients cause problems. The excessive use will result in run-off to water bodies, causing eutrophication, whereas deficit will reduce soil fertility [36].

3.2.5. Recirculate

In the bioeconomy there are different possibilities of recycling. Biobased products can contribute to organic recycling (related to the fourth principle, regenerate) through industrially compostable biobased products as well as in-situ biodegradation, such as with biodegradable mulching films [65,66]. The European EN 13,432 "Packaging: requirements for packaging recoverable through composting and biodegradation" is the standard to comply to for treatment in industrial composting facilities. Applying the digestate from anaerobic digestion is also part of organic recycling (see Figure 6, point 2). The third cycle in Figure 5 also depicts the return of carbon and nutrients after various utilization pathways of biomass in the economy.

Biomass also enters the technical cycle (see Figure 6, blue cycle) and is used in the production of chemicals, plastics and materials. The biobased products can be kept in the technical cycle (see Figure 5, fourth cycle) through reuse and recycling mechanically or chemically (see Figure 6, purple lines). It is preferred to keep the cycles tighter (e.g., reuse rather than recycle) to preserve the value, which is referred to as the power of inner cycle [67]. It should also be aimed to maximize the number of consecutive cycles and/or the time spent in each cycle by extending the product life [68].

Recycling is very well established for paper products, which can be recycled several times [69]. Wood fibers can be recycled (mechanically) five to seven times before the quality becomes too low (fiber becomes too short) to produce new paper products due to physical degradation from repulping and processing. For biobased plastics and other materials made using biobased chemicals, there are two main categories: drop-in and dedicated [70]. The drop-in chemicals are chemically identical to currently used petrochemicals, can feed into the established market and be recycled using the same system in place [6]. For example, polyethylene (PE) and polyethylene terephthalate (PET) produced from biomass can be reused and mechanically recycled together with fossil-based PE and PET with no additional effort [71]. For dedicated chemicals, no directly identical fossil-based counterparts exist (i.e., PLA). For their associated products, the waste management system needs to be adapted to achieve efficient recycling of these products.

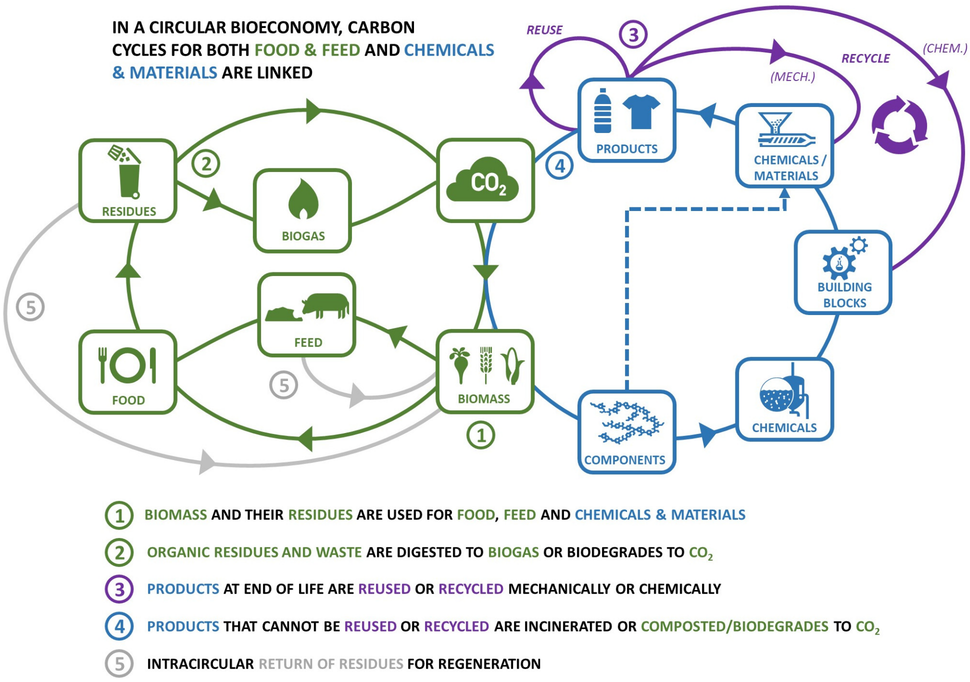

Figure 6. Interconnected cycles in a circular bioeconomy (source: [72]).

3.2.6. Extend the High-Quality Use of Biomass (Including Cascading Use)

It should be aimed to keep the biomass in use as long and at as high a grade as possible. Therefore, it is preferred to preserve the quality while recycling. However, the secondary material attained from recycling is often at a lower quality than the original material due to degradation and contamination [73]. This is called downcycling, which should be minimized. Retaining the highest utility in recirculation is very much dependent on the effectiveness of the collection system and the quality and purity of secondary material. Therefore, products should be designed to enable reuse and high-grade recycling as much as possible. Furthermore, the waste management and recycling systems should focus on providing high-quality recycled material to the economy [74]. Integrating circular economy principles at the design stage (circular by design) will facilitate high-value recovery after use [75].

Furthermore, chemical recycling can be a good approach to avoid downgrading. Chemical recycling allows us to recover building blocks or monomers that plastics are made of and has the advantage of being able to preserve the quality (yields polymer at identical quality to the virgin polymer) [74]. In this way, the cycle gets longer, with additional processing required to acquire to the product from monomers, but the original quality can be preserved. There are many research activities and start-ups working on developing this further [76–79].

Optimizing the time spent in each cycle and the number of consecutive cycles is sought after (by minimizing the quality loss at each application) [80]. In this respect, cascading makes optimal use of biomass in consecutive products. The biomass is ideally used at the highest value and then reused or recycled for the same application as much as possible before moving to lower value applications in the following cascading steps (due to lowering of the quality of the secondary material). Value or quality refers to the functionality based on the inherent and intrinsic material properties such as structure and chemical composition [81].

In Figure 7, this is illustrated for wood. Wood is ideally first used for construction as beams, then can be used to make particle board, paper, chemicals and energy as consecutive products while at each stage maximizing closed loop recycling before moving down to lower quality applications [82]. It will be important to design the products and recycling systems so that it will be possible to extend the high-quality use of the biomass in such a way. Cascading use can provide substantial reduction in use of virgin resources by consecutively replacing virgin material needs with each application step and allow for highly resource-efficient use of biomass [83,84]. Cascading can be observed in current practice in the flow of materials between lumber, paper and energy sectors. There is potential for cascading also in use of textiles. They can be reused multiple times (second-hand apparel) for clothing, and when no longer suitable for this original application, they can be used as fiber-fill in upholstery in the furniture industry and then for insulation in the construction industry [67,85]. Each consecutive application substitutes an inflow of virgin materials into the economy.

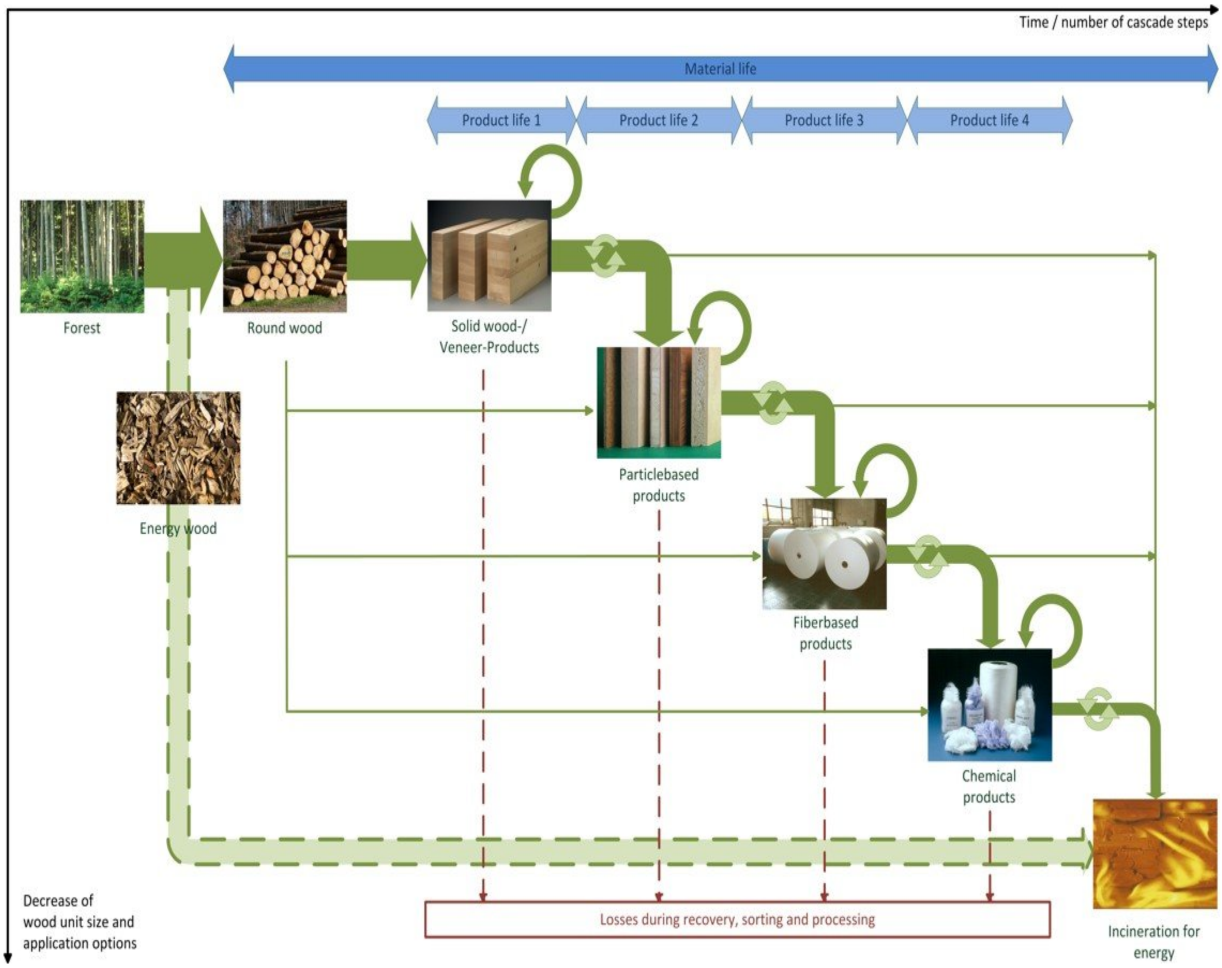

Figure 7. Cascading use of biomass with the example of wood (source: Technical University Munich, 2017 [86]).

3.2.7. What Needs to Be Measured for Monitoring Circularity of Biobased Products

The measurement needs in order to evaluate the circularity performance of biobased products were identified (also included in Table 2). They are divided into two categories, as intrinsic and impact indicators.

The first category refers to indicators providing a measure of intrinsic circularity. This is about what needs to be measured in order to evaluate the circularity performance of biobased products with respect to the six CE principles defined. Linking with the first principle, we would like to minimize virgin fossil feedstock input and substitute the input needed with renewable resources such as biomass. Therefore, the first need concerns here the share of the feedstock that is renewable. Linking with the second and third principles, the second need is a measure of the efficiency of biomass utilization. This includes consideration of multi-output production with biorefining, reduction of waste and valorization of residual streams. The third need is linked with the fourth principle and concerns indicators that measure the degree of regeneration, looking at how well the soil carbon and nutrient cycles are maintained. This also considers organic recycling of biobased products. The fourth need addresses the degree of recirculation (linking with fifth principle), considering how well the loops are closed (by reuse or recycling), thereby minimizing incineration and landfilling. Then, the fifth need concerns measure of utility, which relates to ensuring products stay in the cycle as long as possible in as high a quality as possible (linking with the sixth principle). This also considers cascading use of biomass.

The second category refers to indicators concerning the evaluation of the impact of the transition to the circular economy. While circularity could contribute to improving sustainability, trade-offs exist that need to be addressed [87,88]. One issue is that along the cascade, products can accumulate hazardous substances. When using biobased materials, the presence of these hazardous substances should be considered, as well as their health and safety effects when closing loops. Accordingly, the sixth need is included, which considers measurement of risk of accumulation of hazardous substances (see Table 2). The use of biomass containing hazardous substances can lead to accumulation in biobased products or in the environment where the product is produced or used [54,55]. This can have severe impact on plant, animal or human health [89,90]. They can also enter and concentrate in the food chain [3]. It will therefore be appropriate to consider this as part of the overall assessment to measure such consequential toxicity risks and impacts.

Additionally, to be able to assess whether CE successfully supports sustainable development, all three dimensions of sustainability should be included [27]. Accordingly, the needs 7 to 9 are included in Table 2 to measure effects on environment, economy and society, respectively. As included in the definition by Kirchherr et al., a circular economy should aim at "simultaneously creating environmental quality, economic prosperity and social equity" [20].

4. Discussion

There are currently several challenges faced by biobased products in adhering to these circular economy principles, which are discussed below.

The transition from fossil-based to biobased products requires innovation in new biobased products to be able to meet all the demand currently supplied by fossil-based products. The EC is supporting innovation in new materials, chemicals and processes through research funding. The public–private partnership, the Bio-based Industries Joint Undertaking (BBI-JU), between 2014–2020 was important in the development of a broad spectrum of new, biobased value chains, spanning from simple fossil substitutes to biobased products with novel functionalities [91]. It is now followed up by the Circular Bio-based Europe Joint Undertaking (CBE JU) in the 2021–2031 period with the ambition to accelerate the innovation process as well as market deployment of sustainable biobased solutions [92].

Currently, biomass finds most use for energy and thereby is lost to the circular economy. This is also as the existing renewable energy policy incentivizes use of biomass directly for energy (i.e., RED [53]). This also hampers the establishment of effective wood cascades [6]. Therefore, what is referred to as a "level playing field" is sought after to achieve more efficient allocation of biomass feedstock among chemical/material and energy applications [14]. New policy frameworks need to encourage the cascading use of biomass, where biomass is used for materials and at the end of life (or final stage of the cascade) is released as much as possible for energy use [12,46].

The current collection, recovery and recycling infrastructure is not efficient, which is limiting the extent biobased products can stay in the cycle. Waste processors generally resist processing biobased products, which is hindering the organic or mechanical recycling possibilities of these products [93]. Industrial compostable biobased products still need to find their place and acceptance in the composting facilities. For non-biodegradable products, the preferred end-of-life option is mechanical recycling. However, for dedicated plastics where no chemically identical fossil-based products exist (such as PLA), recycling is not applied although it is technically possible. This is because the volumes are currently too low to make this financially attractive [71]. This is also the case for many other plastics on the market (both petro- and biobased), which end up mostly in mixed recyclates with low value application potential only. Moreover, it is challenging to recycle materials that are painted, coated or treated as the presence of preservatives or glues hamper future applications of the recycled materials [6]. However, they often need to be used for biobased products to extend their durability. Furthermore, multi-layer packaging provides efficient food preservation yet cannot be mechanically recycled.

Cascading mechanisms are currently not accommodated [12]. Creation of an after-use economy is needed that calls for effective infrastructure for collection, transportation and sorting facilities and technologies [74,94]. Cascading use requires the alignment of different markets involving multiple sets of actors along the value chain. The supply of the secondary material is also influenced by the market context and the regulatory framework that are applicable [84]. This raises the question of how cascading use should be governed or steered. Campbell-Johnson et al. consider a steering framework or governance approach organized at the macro scale to guide the cascading decision-making and valorization processes [81]. Moreover, policy mechanisms and instruments are needed to foster cascading use and alleviate the (technical, market, governance) barriers [80,84,95]. Yet, the current EU circular economy policies are geared towards increasing recycling rates [96]. Incentives need to be created to stimulate quality rather than quantity alone [93]. The regulations are, therefore, currently not strong enough to support the use of recycled materials in products of higher value. Besides the requirement for achieving high quality recycling, there is a requirement for policies facilitating the efficient functioning of secondary materials markets [97].

Although potential is seen in the reduction of environmental impacts with cascading use compared to direct use for energy, evidence for this is not well established. There have been several greenhouse gas emission calculations or life cycle analyses carried out to evaluate the environmental impact of cascading use and the influence of a number of cascading steps [98–101]. However, they reported varied results on the environmental impact of cascading use. This is due to the difference in methodological choices made, such as system boundary considered, reference system defined, consequential or attributional approach used, etc. [102]. Accordingly, further research is needed to better understand the benefits and trade-offs where more reliable data and knowledge are generated to be able to validate the assumptions made [94].

Production of biobased products requires natural resources. It is important to achieve a sustainable supply of required quantities of biomass and prevent overexploitation of natural resources and degradation of the ecosystem [13]. A recent EEA report concludes that it is essential to find a balance between valorization of biomass and preserving ecosystem services, including soil quality, biodiversity and water quality and availability [6]. In the forestry sector, the term "sustainable yield" is used, which aims at extracting resources at a rate that does not exceed regeneration capacity to maintain the ecosystem services and long-term productivity of forest ecosystems [103]. Additionally, the quantity and location of nutrients returned is of importance as nutrient imbalance can have severe impact on environment [36]. For example, there is excessive manure production in the Netherlands, which cannot be adequately returned to the soil, whereas there are shortages elsewhere, which require compensation by artificial fertilizers [38].

5. Conclusions

This paper describes circular economy principles for biobased products and identifies what needs to be measured with respect to these principles. It is seen that the bioeconomy and circular economy show synergies and that the bioeconomy is essential for reducing reliance on fossil resources, enabling valorization of wastes and residues and providing possibility of cascading use. To improve the circularity of biomass use in the bioeconomy, there are several cycles that need to be optimized or extended. In order to facilitate the transition towards a sustainable biobased circular economy, an enabling policy framework is required. A level playing field needs to be established between energy and material use of biomass. The cascading use of biomass needs to be encouraged and should lead to energy use in end of life. Furthermore, in the policy context for recycling, the quality aspect needs to be stimulated rather than quantity alone. The biobased products need to find their place and acceptance in the waste processing facilities to reach their intended end-of-life option. First steps in policy development have already been taken but it is important that these EU policy instruments are also transposed to national and regional levels. There is a requirement to link and align bioeconomy, circular economy and sustainability strategies in policies at different scales (municipal, national, EU).

It is highlighted in this paper that assessments should complement intrinsic circularity indicators with sustainability indicators and risk assessment on hazardous substances to yield the multi-dimensional performance of the products. This will prevent burden shifting (reducing resource use at the expense of increased emissions) and show whether the adoption of a circular strategy would simultaneously increase the sustainability of an existing system [104]. Further research is therefore encouraged on the combination of circularity measures and life cycle sustainability indicators. This holistic assessment will allow the discussion of trade-offs and would provide informed decisions on what CE activities should be favored for sustainable development [105].

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References

1. International Resource Panel; United Nations Environmental Programme. *Global Resources Outlook 2019: Natural Resources for the Future We Want: A Report of the International Resource Panel*; International Resource Panel: Nairobi, Kenya, 2019.
2. Jurgilevich, A.; Birge, T.; Kentala-Lehtonen, J.; Korhonen-Kurki, K.; Pietikäinen, J.; Saikku, L.; Schösler, H. Transition towards Circular Economy in the Food System. *Sustainability* **2016**, *8*, 69. [CrossRef]
3. Ellen MacArthur Foundation. *Circularity Indicators: An Approach to Measure Circularity: Methodology*; Ellen MacArthur Foundation: Cowes, UK, 2019.
4. European Commission. *Living Well, within the Limits of Our Planet: 7th EAP—The New General Union Environment Action Programme to 2020*; European Commission: Brussels, Belgium, 2013.
5. European Commission. *Closing the Loop—An EU Action Plan for the Circular Economy*; COM(2015) 614 Final; European Commission: Brussels, Belgium, 2015.

6. European Environmental Agency. *The Circular Economy and the Bioeconomy: Partners in Sustainability*; European Environmental Agency Report No. 8; European Environmental Agency: Copenhagen, Denmark, 2018.
7. European Commission. *Innovating for Sustainable Growth: A Bioeconomy for Europe*; European Commission: Brussels, Belgium, 2012.
8. European Commission. *A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment*; Updated Bioeconomy Strategy COM(2018) 673 Final; European Commission: Brussels, Belgium, 2018.
9. European Commission. *European Green Deal*; COM(2019) 640 Final; European Commission: Brussels, Belgium, 2019.
10. European Commission. *A New Circular Economy Action Plan: For a Cleaner and More Competitive Europe*; COM(2020) 98 Final; European Commission: Brussels, Belgium, 2020.
11. European Commission. *Measuring Progress towards Circular Economy in the European Union—Key Indicators for a Monitoring Framework*; SWD(2018) 17 Final; European Commission: Strasbourg, France, 2018.
12. Carus, M.; Dammer, L. *The "Circular Bioeconomy"—Concepts, Opportunities and Limitations*; Nova Paper #9 on Bio-Based Economy; Nova-Institut: Hurth, Germany, 2018.
13. Hetemäki, L.; Hanewinkel, M.; Muys, B.; Ollikainen, M.; Palahí, M.; Trasobares, A. *Leading the Way to a European Circular Bioeconomy Strategy*; From Science to Policy 5; European Forest Institute: Joensuu, Finland, 2017.
14. Philp, J.; Winickoff, D. Realising the Circular Bioeconomy. In *OECD Science, Technology and Industry Policy Papers, No. 60*; OECD Publishing: Paris, France, 2018.
15. Stegmann, P.; Londo, M.; Junginger, M. The Circular Bioeconomy: Its Elements and Role in European Bioeconomy Clusters. *Resour. Conserv. Recycl. X* **2020**, *6*, 100029. [CrossRef]
16. European Commission. *A Clean Planet for All—A European Long-Term Strategic Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*; COM/2018/773 Final; European Commission: Brussels, Belgium, 2018.
17. European Environmental Agency. *Circular Economy in Europe—Developing the Knowledge Base*; European Environmental Agency Report No. 2; Publications Office of the European Union: Luxembourg, 2016.
18. Potting, J.; Hekkert, M.; Worrell, E.; Hanemaaijer, A. *Circular Economy: Measuring Innovation in the Product Chain*; Policy Report; PBL Netherlands Environmental Assessment Agency: The Hague, The Netherlands, 2017.
19. Reike, D.; Vermeulen, W.J.V.; Witjes, S. 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. *Resour. Conserv. Recycl.* **2018**, *135*, 246–264. [CrossRef]
20. Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the Circular Economy: An Analysis of 114 Definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [CrossRef]
21. *EN 16575:2014*; Bio-Based Products—Vocabulary. European Committee for Standardization: Brussels, Belgium, 2014.
22. Ellen MacArthur Foundation Circular Economy Systems Diagram. Available online: https://ellenmacarthurfoundation.org/circular-economy-diagram (accessed on 3 December 2021).
23. Page, M.J.; Moher, D.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. PRISMA 2020 Explanation and Elaboration: Updated Guidance and Exemplars for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n160. [CrossRef]
24. *G8 Environment Ministers Meeting: Kobe 3R Action Plan*; G7 Information Centre: Kobe, Japan, 2008.
25. European Commission. *Waste Framework Directive: Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives*; European Commission: Brussels, Belgium, 2008.
26. Elia, V.; Gnoni, M.G.; Tornese, F. Measuring Circular Economy Strategies through Index Methods: A Critical Analysis. *J. Clean. Prod.* **2017**, *142*, 2741–2751. [CrossRef]
27. Corona, B.; Shen, L.; Reike, D.; Rosales Carreón, J.; Worrell, E. Towards Sustainable Development through the Circular Economy—A Review and Critical Assessment on Current Circularity Metrics. *Resour. Conserv. Recycl.* **2019**, *151*, 104498. [CrossRef]
28. 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]
29. Boyer, R.H.W.; Mellquist, A.C.; Williander, M.; Fallahi, S.; Nyström, T.; Linder, M.; Algurén, P.; Vanacore, E.; Hunka, A.D.; Rex, E.; et al. Three-Dimensional Product Circularity. *J. Ind. Ecol.* **2021**, *25*, 824–833. [CrossRef]
30. Saidani, M.; Yannou, B.; Leroy, Y.; Cluzel, F. How to Assess Product Performance in the Circular Economy? *Proposed Requirements for the Design of a Circularity Measurement Framework. Recycling* **2017**, *2*, 6. [CrossRef]
31. Alamerew, Y.A.; Kambanou, M.L.; Sakao, T.; Brissaud, D. A Multi-Criteria Evaluation Method of Product-Level Circularity Strategies. *Sustainability* **2020**, *12*, 5129. [CrossRef]
32. 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]
33. Jerome, A.; Helander, H.; Ljunggren, M.; Janssen, M. Mapping and Testing Circular Economy Product-Level Indicators: A Critical Review. *Resour. Conserv. Recycl.* **2022**, *178*, 106080. [CrossRef]
34. Ortiz-de-Montellano, C.G.S.; van der Meer, Y. A Theoretical Framework for Circular Processes and Circular Impacts Through a Comprehensive Review of Indicators. *Glob. J. Flex. Syst. Manag.* **2022**, *23*, 291–314. [CrossRef]
35. The European Bioeconomy Alliance. *Bioeconomy—A Motor for the Circular Economy*; The European Bioeconomy Alliance: Brussels, Belgium, 2016.

36. Navare, K.; Muys, B.; Vrancken, K.C.; Van Acker, K. Circular Economy Monitoring—How to Make It Apt for Biological Cycles? *Resour. Conserv. Recycl.* **2021**, *170*, 105563. [CrossRef]
37. Kardung, M.; Cingiz, K.; Costenoble, O.; Delahaye, R.; Heijman, W.; Lovrić, M.; van Leeuwen, M.; M'barek, R.; van Meijl, H.; Piotrowski, S.; et al. Development of the Circular Bioeconomy: Drivers and Indicators. *Sustainability* **2021**, *13*, 413. [CrossRef]
38. Bos, H.L.; Broeze, J. Circular Bio-Based Production Systems in the Context of Current Biomass and Fossil Demand. *Biofuels Bioprod. Biorefining* **2020**, *14*, 187–197. [CrossRef]
39. Muscat, A.; de Olde, E.M.; Ripoll-Bosch, R.; Van Zanten, H.H.E.; Metze, T.A.P.; Termeer, C.J.A.M.; van Ittersum, M.K.; de Boer, I.J.M. Principles, Drivers and Opportunities of a Circular Bioeconomy. *Nat. Food* **2021**, *2*, 561–566. [CrossRef]
40. Brandão, A.S.; Gonçalves, A.; Santos, J.M.R.C.A. Circular Bioeconomy Strategies: From Scientific Research to Commercially Viable Products. *J. Clean. Prod.* **2021**, *295*, 126407. [CrossRef]
41. Saidani, M.; Yannou, B.; Leroy, Y.; Cluzel, F.; Kendall, A. A Taxonomy of Circular Economy Indicators. *J. Clean. Prod.* **2019**, *207*, 542–559. [CrossRef]
42. Van Ree, R.; de Jong, E. *Task 42 Biorefining in a Future BioEconomy*, IEA Bioenergy ExCo 2019: 08I; IEA Bioenergy: Paris, France, 2019.
43. Ellen MacArthur Foundation. *Completing the Picture: How the Circular Economy Tackles Climate Change*; Ellen MacArthur Foundation: Cowes, UK, 2019.
44. German Environmental Agency (UBA). *Biomass Cascades: Increasing Resource Efficiency by Cascading Use of Biomass—From Theory to Practice*; German Environmental Agency: Dessau-Roßlau, Germany, 2017.
45. Carus, M.; Raschka, A. *Renewable Carbon Is Key to a Sustainable and Future-Oriented Chemical Industry*; Nova Paper #10 on Bio-Based Economy; Nova-Institut: Hurth, Germany, 2018.
46. Social Economic Council. *Biomass in the Balance: A Sustainability Framework for High-Value Use of Bio-Based Raw Materials*; Social Economic Council Advisory Report 20/07; Social Economic Council: The Hague, The Netherlands, 2020.
47. Dutch Government. *A Circular Economy in the Netherlands by 2050 Government-Wide Programme for a Circular Economy*; The Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs, also on behalf of the Ministry of Foreign Affairs and the Ministry of the Interior and Kingdom Relations: The Hague, The Netherlands, 2016.
48. Carus, M.; Skoczinski, P.; Dammer, L.; vom Berg, C.; Raschka, A.; Breitmayer, E. *Hitchhiker's Guide to Carbon Capture and Utilisation (CCU)*; Nova Paper #11 on Bio-Based Economy; Nova-Institut: Hurth, Germany, 2019.
49. Muscat, A.; de Olde, E.M.; de Boer, I.J.M.; Ripoll-Bosch, R. The Battle for Biomass: A Systematic Review of Food-Feed-Fuel Competition. *Glob. Food Sec.* **2020**, *25*, 100330. [CrossRef]
50. Van Groenestijn, J.; Harmsen, P.; Bos, H. *Biomass for the Circular Economy: Everything You Wanted to Know about Biomass but Were Afraid to Ask*; Wageningen Food & Biobased Research: Wageningen, The Netherlands, 2019.
51. De Jong, E.; Higson, A.; Walsh, P.; Wellisch, M. Bio-Based Chemicals: Value Added Products from Biorefineries—Task 42 Biorefinery; IEA Bioenergy Task 42; IEA Bioenergy, 2012.
52. Platt, R.; Bauen, A.; Reumerman, P.; Geier, C.; Van Ree, R.; Gursel, I.V.; Garcia, L.; Behrens, M.; von Bothmer, P.; Howes, J.; et al. *EU Biorefinery Outlook to 2030—Studies on Support to Research and Innovation Policy in the Area of Bio-Based Products and Services*; Publications Office of the European Union: Luxembourg, 2021.
53. European Commission. *Directive (EU) 2018/2001 of the European Parlement and the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (Recast)*; European Commission: Brussels, Belgium, 2018.
54. Evangelou, M.W.H.; Papazoglou, E.G.; Robinson, B.H.; Schulin, R. Phytomanagement: Phytoremediation and the Production of Biomass for Economic Revenue on Contaminated Land. In *Phytoremediation: Management of Environmental Contaminants*; Ansari, A., Gill, S., Gill, R., Lanza, G., Newman, L., Eds.; Springer: Cham, Switzerland, 2015; Volume 1, pp. 115–132. ISBN 9783319103952.
55. Abhilash, P.C.; Tripathi, V.; Edrisi, S.A.; Dubey, R.K.; Bakshi, M.; Dubey, P.K.; Singh, H.B.; Ebbs, S.D. Sustainability of Crop Production from Polluted Lands. *Energy Ecol. Environ.* **2016**, *1*, 54–65. [CrossRef]
56. Dastyar, W.; Raheem, A.; He, J.; Zhao, M. Biofuel Production Using Thermochemical Conversion of Heavy Metal-Contaminated Biomass (HMCB) Harvested from Phytoextraction Process. *Chem. Eng. J.* **2019**, *358*, 759–785. [CrossRef]
57. Fernando-foncillas, C.; Estevez, M.M.; Uellendahl, H.; Varrone, C. Co-Management of Sewage Sludge and Other Organic Wastes: A Scandinavian Case Study. *Energies* **2021**, *14*, 3411. [CrossRef]
58. Netherlands Enterprise Agency (RVO). *Guidance on the Classification of Biomass: Categories and NTA 8003 Codes under the SDE+ Scheme*; Netherlands Enterprise Agency: The Hague, The Netherlands, 2019.
59. Dahiya, S.; Kumar, A.N.; Shanthi Sravan, J.; Chatterjee, S.; Sarkar, O.; Mohan, S.V. Food Waste Biorefinery: Sustainable Strategy for Circular Bioeconomy. *Bioresour. Technol.* **2018**, *248*, 2–12. [CrossRef]
60. Bruins, M. Technical Examples on Added Value Generation. Available online: https://power4bio.eu/wp-content/uploads/2020/11/POWER4BIO_WUR_FoodFeed-2-Examples-added-value-generation.pdf (accessed on 13 December 2021).
61. POWER4BIO Catalogue of Bioeconomy Solutions. Available online: https://www.bio-based-solutions.eu/#/ (accessed on 13 December 2021).
62. Turmel, M.S.; Speratti, A.; Baudron, F.; Verhulst, N.; Govaerts, B. Crop Residue Management and Soil Health: A Systems Analysis. *Agric. Syst.* **2015**, *134*, 6–16. [CrossRef]
63. European Environment Agency. *Bio-Waste in Europe—Turning Challenges into Opportunities*; Publications Office of the European Union: Luxembourg, 2020.

64. Coppens, J.; Meers, E.; Boon, N.; Buysse, J.; Vlaeminck, S.E. Follow the N and P Road: High-Resolution Nutrient Flow Analysis of the Flanders Region as Precursor for Sustainable Resource Management. *Resour. Conserv. Recycl.* **2016**, *115*, 9–21. [CrossRef]
65. Van den Oever, M.; Molenveld, K.; van der Zee, M.; Bos, H. *Bio-Based and Biodegradable Plastics: Facts and Figures*; Wageningen Food and Biobased Research: Wageningen, The Netherlands, 2017.
66. Di Bartolo, A.; Infurna, G.; Dintcheva, N.T. A Review of Bioplastics and Their Adoption in the Circular Economy. *Polymers* **2021**, *13*, 1229. [CrossRef]
67. Ellen MacArthur Foundation. *Towards the Circular Economy. Economic and Business Rationale for an Accelerated Transition*; Ellen MacArthur Foundation: Cowes, UK, 2013. Available online: https://ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an (accessed on 13 December 2021).
68. Ellen MacArthur Foundation. *Towards a Circular Economy: Business Rationale for an Accelerated Transition*; Ellen MacArthur Foundation: Cowes, UK, 2015. Available online: https://ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition (accessed on 13 December 2021).
69. Mantau, U. Wood Flow Analysis: Quantification of Resource Potentials, Cascades and Carbon Effects. *Biomass Bioenergy* **2015**, *79*, 28–38. [CrossRef]
70. Spekreijse, J.; Lammens, T.; Parisi, C.; Ronzon, T.; Vis, M. *Insights into the European Market of Bio-Based Chemicals: Analysis Based on Ten Key Product Categories*; Publications Office of the European Union: Luxembourg, 2019.
71. Odegard, I.; Nusselder, S.; Lindgreen, E.R.; Bergsma, G.; de Graaff, L. *Biobased Plastics in a Circular Economy*; CE Delft: Delft, The Netherlands, 2017.
72. Van Es, D.S.; Blaauw, R. *Biobased Materials and Chemicals for Relieving and Replacing the Fossil Feedstock System (Project KB34-3B-1)*; WUR Knowledge Base Program, Circular and Climate Neutral Society: Wageningen, The Netherlands, 2021.
73. Allwood, J.M. Squaring the Circular Economy: The Role of Recycling within a Hierarchy of Material Management Strategies. In *Handbook of Recycling*; State-of-the-art for Practitioners, Analysts, and Scientists; Elsevier: Amsterdam, The Netherlands, 2014; pp. 445–477. [CrossRef]
74. Crippa, M.; De Wilde, B.; Koopmans, R.; Leyssens, J.; Muncke, J.; Ritschkoff, A.-C.; Van Doorsselaer, K.; Velis, C.; Wagner, M. *A Circular Economy for Plastics—Insights from Research and Innovation to Inform Policy and Funding Decisions*; Publications Office of the European Union: Luxembourg, 2019.
75. European Environment Agency. *Circular by Design: Products in the Circular Economy*; European Environmental Agency, Publications Office of the European Union: Luxembourg, 2017.
76. Kosloski-Oh, S.C.; Wood, Z.A.; Manjarrez, Y.; De Los Rios, J.P.; Fieser, M.E. Catalytic Methods for Chemical Recycling or Upcycling of Commercial Polymers. *Mater. Horiz.* **2021**, *8*, 1084–1129. [CrossRef] [PubMed]
77. Thiounn, T.; Smith, R.C. Advances and Approaches for Chemical Recycling of Plastic Waste. *J. Polym. Sci.* **2020**, *58*, 1347–1364. [CrossRef]
78. Coates, G.W.; Getzler, Y.D.Y.L. Chemical Recycling to Monomer for an Ideal, Circular Polymer Economy. *Nat. Rev. Mater.* **2020**, *5*, 501–516. [CrossRef]
79. Collias, D.I.; James, M.I.; Layman, J.M. *Circular Economy of Polymers: Topics in Recycling Technologies*; American Chemical Society: Washington, DC, USA, 2021; Volume 1391.
80. Keegan, D.; Kretschmer, B.; Elbersen, B.; Panoutsou, C. Cascading Use: A Systematic Approach to Biomass beyond the Energy Sector. *Biofuels Bioprod. Biorefining* **2013**, *7*, 193–206. [CrossRef]
81. Campbell-Johnston, K.; Vermeulen, W.J.V.; Reike, D.; Brullot, S. The Circular Economy and Cascading: Towards a Framework. *Resour. Conserv. Recycl. X* **2020**, *7*, 100038. [CrossRef]
82. Höglmeier, K.; Weber-Blaschke, G.; Richter, K. Potentials for Cascading of Recovered Wood from Building Deconstruction—A Case Study for South-East Germany. *Resour. Conserv. Recycl.* **2013**, *78*, 81–91. [CrossRef]
83. Risse, M.; Weber-Blaschke, G.; Richter, K. Resource Efficiency of Multifunctional Wood Cascade Chains Using LCA and Exergy Analysis, Exemplified by a Case Study for Germany. *Resour. Conserv. Recycl.* **2017**, *126*, 141–152. [CrossRef]
84. Vis, M.; Mantau, U.; Allen, B. *Study on the Optimised Cascading Use of Wood*; No 394/PP/ENT/RCH/14/7689; Publications Office of the European Union: Luxembourg, 2016; ISBN 9789279577253.
85. Shirvanimoghaddam, K.; Motamed, B.; Ramakrishna, S.; Naebe, M. Death by Waste: Fashion and Textile Circular Economy Case. *Sci. Total Environ.* **2020**, *718*, 137317. [CrossRef]
86. Technical University Munich. Cascading Use of Wood to Ensure Sustainability. 12 December 2017. Phys.org. Available online: https://phys.org/news/2017-12-cascading-wood-sustainability.html (accessed on 13 December 2021).
87. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.P.; Hultink, E.J. The Circular Economy—A New Sustainability Paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768. [CrossRef]
88. Schaubroeck, T. Circular Economy Practices May Not Always Lead to Lower Criticality or More Sustainability; Analysis and Guidance Is Needed per Case. *Resour. Conserv. Recycl.* **2020**, *162*, 104977. [CrossRef]
89. Marini, M.; Angouria-Tsorochidou, E.; Caro, D.; Thomsen, M. Daily Intake of Heavy Metals and Minerals in Food—A Case Study of Four Danish Dietary Profiles. *J. Clean. Prod.* **2021**, *280*, 124279. [CrossRef]
90. Thomsen, M.; Faber, J.H.; Sorensen, P.B. Soil Ecosystem Health and Services—Evaluation of Ecological Indicators Susceptible to Chemical Stressors. *Ecol. Indic.* **2012**, *16*, 67–75. [CrossRef]

91. Lange, L.; Connor, K.O.; Arason, S.; Bundgård-Jørgensen, U.; Canalis, A.; Carrez, D.; Gallagher, J.; Gøtke, N.; Huyghe, C.; Jarry, B.; et al. Developing a Sustainable and Circular Bio-Based Economy in EU: By Partnering Across Sectors, Upscaling and Using New Knowledge Faster, and For the Benefit of Climate, Environment & Biodiversity, and People & Business. *Front. Bioeng. Biotechnol.* **2021**, *8*, 1456. [CrossRef]
92. The Circular Bio-Based Europe Joint Undertaking (CBE JU). Available online: https://www.bbi.europa.eu/about/circular-bio-based-europe-joint-undertaking-cbe-ju (accessed on 21 December 2021).
93. Ladu, L.; Clavell, J.; Quitzow, R.; Costenoble, O.; Vrins, M.; van den Berg, J.; Babayan, T.; vom Berg, C.; Dammer, L.; Partanen, A.; et al. *STAR4BBI D4.4 Regulation Action Plan*; Bio-based Industries Consortium: Brussels, Belgium, 2019.
94. Jarre, M.; Petit-Boix, A.; Priefer, C.; Meyer, R.; Leipold, S. Transforming the Bio-Based Sector towards a Circular Economy—What Can We Learn from Wood Cascading? *For. Policy Econ.* **2020**, *110*, 101872. [CrossRef]
95. Dammer, L.; Bowyer, C.; Breitmayer, E.; Eder, A.; Nanni, S.; Allen, B.; Carus, M.; Essel, R. *Mapping Study on the Cascading Use of Wood Products*; WWF—World Wide Fund For Nature: Gland, Switzerland, 2016.
96. Calisto Friant, M.; Vermeulen, W.J.V.; Salomone, R. Analysing European Union Circular Economy Policies: Words versus Actions. *Sustain. Prod. Consum.* **2021**, *27*, 337–353. [CrossRef]
97. Milios, L. Advancing to a Circular Economy: Three Essential Ingredients for a Comprehensive Policy Mix. *Sustain. Sci.* **2018**, *13*, 861–878. [CrossRef]
98. Bais-Moleman, A.L.; Sikkema, R.; Vis, M.; Reumerman, P.; Theurl, M.C.; Erb, K.H. Assessing Wood Use Efficiency and Greenhouse Gas Emissions of Wood Product Cascading in the European Union. *J. Clean. Prod.* **2018**, *172*, 3942–3954. [CrossRef]
99. Höglmeier, K.; Weber-Blaschke, G.; Richter, K. Utilization of Recovered Wood in Cascades versus Utilization of Primary Wood—A Comparison with Life Cycle Assessment Using System Expansion. *Int. J. Life Cycle Assess.* **2014**, *19*, 1755–1766. [CrossRef]
100. Höglmeier, K.; Steubing, B.; Weber-Blaschke, G.; Richter, K. LCA-Based Optimization of Wood Utilization under Special Consideration of a Cascading Use of Wood. *J. Environ. Manag.* **2015**, *152*, 158–170. [CrossRef]
101. Sikkema, R.; Junginger, M.; McFarlane, P.; Faaij, A. The GHG Contribution of the Cascaded Use of Harvested Wood Products in Comparison with the Use of Wood for Energy—A Case Study on Available Forest Resources in Canada. *Environ. Sci. Policy* **2013**, *31*, 96–108. [CrossRef]
102. Thonemann, N.; Schumann, M. Environmental Impacts of Wood-Based Products under Consideration of Cascade Utilization: A Systematic Literature Review. *J. Clean. Prod.* **2018**, *172*, 4181–4188. [CrossRef]
103. Muys, B.; Masiero, M.; Achten, W. Sustainability Issues of Using Forests as a Bioenergy Resource. In *Forest Bioenergy for Europe*; Pelkonen, P., Mustonen, M., Asikainen, A., Egnell, G., Kant, P., Leduc, S., Pettenella, D., Eds.; European Forest Institute: Joensuu, Finland, 2014; pp. 90–97. ISBN 9789525980103.
104. Harris, S.; Martin, M.; Diener, D. Circularity for Circularity's Sake? *Scoping Review of Assessment Methods for Environmental Performance in the Circular Economy. Sustain. Prod. Consum.* **2021**, *26*, 172–186. [CrossRef]
105. Blum, N.U.; Haupt, M.; Bening, C.R. Why "Circular" Doesn't Always Mean "Sustainable". *Resour. Conserv. Recycl.* **2020**, *162*, 105042. [CrossRef]