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BioReCer

Biological Resources Certifications Schemes

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Authors

Name	Organisation	Email
Eliza Nika	Imperial College London (ICL)	e.nika@imperial.ac.uk
Vasileia Vasilaki	ICL	v.vasilaki@imperial.ac.uk
David Renfrew	ICL	d.renfrew@imperial.ac.uk
Evina Katsou	ICL	e.katsou@imperial.ac.uk

Type

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Lead beneficiary

Imperial College London (Eliza Nika, David Renfrew, Vasileia Vasilaki, Evina Katsou).

Internal reviewer(s)

Name	**Organization**	**Email**
Lucia Jimena Gonzalez Monjardin	Cetaqua	lucia-jimena.gonzalez@cetaqua.com
Carla Carreira Garcia	Cetaqua	carla.carreira.ext@cetaqua.com
Sofía Estévez Rivadulla	University of Santiago de Compostela	sofia.estevez.rivadulla@usc.es
Kyu hee Do	Meo Carbon Solutions GmbH	do@meo-carbon.com
Monica Pandey	Meo Carbon Solutions GmbH	pandey@meo-carbon.com
Nadja Wulff	Nova Institute	nadja.wulff@nova-institut.de
Isabel Burdallo	Research Institutes of Sweden	isabel.burdallo@ri.se

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Publishable executive summary

The BioReCer project is dedicated to ensuring the environmental performance and traceability of biological feedstocks and bio-based products, and a critical aspect of this is identifying and selecting indicators that measure and assess their circularity. The primary objective is to incorporate these indicators into certification schemes, thereby addressing significant gaps in current circular indicators, which are predominantly designed for technical systems and fossil-based products. These traditional indicators often fail to capture the unique characteristics of the bio-based sector, thus hindering its transition to a CE. The project seeks to equip the bio-based industry with the necessary tools to monitor its circularity transition, demonstrate circular advancements, and gain public and customer acceptance, ultimately enhancing economic incentives.

Since the project's inception, extensive research and analysis have been undertaken to identify the limitations of existing circularity indicators and their applicability to bio-based products. This effort includes a comprehensive review of current literature and standards, such as the newly developed ISO 59000 series, which provides a foundational framework for circularity assessment across various sectors. However, these standards need adaptation to address the specific requirements of the bio-based sector. To this end, the BioReCer project has developed a methodology to refine these indicators, ensuring they are tailored to the unique characteristics and lifecycle stages of bio-based products.

A critical output is the development of a comprehensive set of circular indicators, which encompass the entire lifecycle of bio-based products, from raw material extraction to end-of-life management, ensuring a holistic approach to circularity assessment. By focusing on the entire value chain, the project acknowledges that the feedstock for one actor in the supply chain is often the product of the previous actor. This interconnected approach is crucial for maintaining circularity throughout the lifecycle of bio-based products.

The project has also identified the need to distinguish between intrinsic and consequential circularity indicators. Intrinsic circularity indicators focus on the inherent qualities of products and processes that contribute to circularity, such as recyclability, durability, and renewable content. Consequential circularity indicators, on the other hand, measure the broader impacts and outcomes of circular practices, such as the reduction in environmental footprints and the creation of sustainable economic opportunities. This deliverable focuses primarily on intrinsic circularity indicators to avoid duplicating efforts detailed in Deliverable 2.2 – Modified Assessment Methodologies, which addresses sustainability criteria and indicators. Thereby, the deliverables can be used in combination to measure intrinsic

(assessment of physical resource loops and products) and consequential (sustainability dimensions) circularity to satisfy standardised assessments, such as the new ISO59020.

An essential aspect of the project's work is the recognition that technical systems are increasingly pressured to replace fossil-based resources with bio-based feedstocks, often assumed to be sustainable and circular by definition. The BioReCer project underscores the importance of addressing both biological and technical cycles in the bio-based sector. The biological cycle involves renewable resources undergoing natural processes like growth, decay, and nutrient recycling, while the technical cycle focuses on maintaining the value of non-biodegradable products through strategies such as recycling, remanufacturing, and reuse. By balancing these cycles, the project aims to optimize the circularity and sustainability of bio-based products. However, without appropriate circular indicators, there is a risk of shifting the burden to localized impacts due to potentially imprudent use of bio-based resources.

Therefore, the BioReCer project aims to mitigate these risks by providing a set of appropriate and holistic circular indicators for bio-based products, thereby positioning the bio-based sector at the forefront of the circular economy (CE) transition. The final results of the BioReCer project are expected to include a validated set of circular indicators that can be seamlessly integrated into existing certification schemes. Integrating these indicators into certification schemes can significantly benefit the bio-based industry by providing guidance as to which indicators must be utilised to officially verify their products as circular, thus increasing customer trust and acceptance.

Looking ahead, the project will focus on the application, testing, and validation of the selected indicators in various BioReCer case studies, as outlined in the case study reports (Deliverables 6.1 and 6.2), and integration into BioReCer's digital solutions, as detailed in WP3 and WP5 deliverables. The emphasis on the entire value chain ensures that circularity is maintained throughout the lifecycle of bio-based products, from raw material extraction to end-of-life management.

In summary, the BioReCer project is dedicated to advancing the CE within the bio-based sector by developing and integrating tailored circular indicators. These indicators are designed to capture the unique characteristics of bio-based products and their entire lifecycle, ensuring a comprehensive and accurate assessment of their circularity. By doing so, the project aims to enhance the bio-based industry's sustainability practices, generate new jobs, increase customer trust, and drive the transition towards a more sustainable and resilient CE.

For more information about the BioReCer project, including updates on our progress and access to project deliverables, please visit our website at https://biorecer.eu.

1 Terms and Definitions

To ensure clarity and consistency throughout this deliverable, this section provides definitions for key terms related to circularity and sustainability in the bio-based sector. These terms are listed in alphabetical order and are integral to understanding the methodologies, indicators, and frameworks discussed, including some that have been developed and/or tailored to the needs of the bio-based sector meaning they are appropriate within the context of the BioReCer project. This glossary aims to facilitate a common understanding among readers and stakeholders, ensuring that the concepts and terminologies used are interpreted accurately and uniformly.

Bio-based: Refers to products and materials derived from renewable biological resources, such as plants, animals, and microorganisms. These resources are utilized to produce various products including food, feed, bio-based materials, chemicals, and bioenergy.

Biological Cycle: In the bio-based sector, this cycle involves renewable resources undergoing natural processes like growth, decay, and nutrient recycling. Products derived from biological sources can biodegrade and return nutrients to the biosphere, thus supporting the growth of new biological resources.

By-product: A secondary product derived from a manufacturing process or chemical reaction that is not the primary product or service being produced.

Cascading Use: Cascading use involves the sequential utilization of biomass for multiple applications to maximize resource efficiency. It prioritizes high-value applications first, utilizes the entire feedstock along with all co-products and by-products, and ensures the successive use of biomass for different purposes, thereby minimizing waste and maximizing benefits.

Circularity: A systemic approach to economic development designed to benefit businesses, society, and the environment. Unlike the linear "take, make, dispose" model, a CE aims to redefine growth, focusing on positive society-wide benefits by designing out waste and pollution, keeping products and materials in use, and regenerating natural systems.

Consequential Circularity Indicators: Indicators that measure the broader impacts and outcomes of circular practices, such as the reduction in environmental footprints or the creation of sustainable economic opportunities.

Consumable Product: Products that are intended to be used up or discarded after a single or limited use, such as food, fuel, and personal care items.

Co-product: One of multiple products derived from a single production process or system, using the same feedstock (or different parts of the same feedstock) with the other co-products. Co-products are usually of similar value and importance as the main product.

Criterion: Objective that must be met to achieve the aspirational goal or principle that governs decisions and behaviour.

Durable Product: Products designed for long-term use, which can be repaired, reused, or upgraded, such as textiles, plastics, building materials and furniture.

Feedstock: Raw material used to produce various bio-based products.

Final Producer: The last actor in the production chain who generates the end product that is directly provided to the user or consumer.

Indicator: A metric used to quantify the performance or impact of a specific aspect of a product, process, or system. In this context, it refers to measures of circularity.

Intermediate Producer: An actor in the production chain who generates products requiring further treatment or processing to create the final product in the supply chain.

Intrinsic Circularity Indicators: Indicators that focus on the inherent qualities of products and processes that contribute to circularity, such as recyclability, durability, and renewable content.

Lifecycle: The complete process a product undergoes from the extraction of raw materials to its disposal or recycling. This includes stages such as material extraction, production, distribution, use, and end-of-life management.

Post-consumer Producer: Producers involved in the processing and management of products after their initial use by consumers. They can be either intermediate or final producers.

Pre-consumer Producer: Producers who obtain their main feedstock from upstream actors (either virgin or residues) and generate products requiring further processing (intermediate) or the final product (final) in the supply chain.

Primary Producer: Producers who generate products and by-products of biological origin to provide them to the next actor in the supply chain. This includes forestry producers, agricultural producers, and fish farmers.

Product: Any good or service that is produced or manufactured by any actor of the supply chain and offered for sale.

Residue: Materials remaining after the primary processing of raw materials, which can often be utilized in other processes or as a secondary feedstock.

Sustainable Biomass Production: Ability to continuously meet resource requirements of humans whilst safeguarding the environment by implementing relevant legal frameworks to protect key primary resources, soil quality, species biodiversity, and environment sinks.

Technical Cycle: Involves products and materials that are not biodegradable and must be managed within the technical cycle, focusing on maintaining the value of products, components, and materials through strategies such as recycling, remanufacturing, and reuse.

2 Introduction to Circularity Measurement and Assessment in Bio-based Products

The measurement of circularity for bio-based products is essential for driving the transition towards a sustainable CE. Unlike traditional linear models of production and consumption, circular models emphasize resource efficiency, waste reduction, and the continuous use of materials. For bio-based products, which derive from renewable biological resources, measuring circularity ensures that these products contribute positively to environmental sustainability and resource conservation.

The state of the art in circularity assessment is guided by newly developed and recently published standards, notably the ISO 59000 series, which provides frameworks for assessing and improving circularity across various sectors. These standards outline methodologies for measuring resource efficiency, waste reduction, and life cycle impacts, setting a foundation for organizations to track and enhance their circular performance. However, these standards, and other frameworks such as the Circular Transitions Indicators published by wbcsd, have primarily been developed with industrial systems in mind, mitigating the requirements of bio-based systems. Despite the progress made with standards like ISO 59000, there are significant gaps when these are applied to bio-based products. Existing circularity indicators in current literature and standards often overlook the unique characteristics and lifecycle stages of bio-based materials. For instance, bio-based products have specificities in their production, usage, and disposal phases that differ from non-bio-based products. Differences stem from the CE goals of technical cycles, which aims to mitigate extraction and disposal entirely, and biological cycles, which demands sustainable production and safe return to the environment. This oversight hinders the accurate assessment of their circularity, making it challenging for the bio-based sector to demonstrate its sustainability and economic benefits effectively.

Circularity measurement and assessment in the context of both technical and bio-based products must be grounded in systems thinking, a core principle of the CE. Systems thinking emphasizes the interconnectedness of various components within an ecosystem, considering the full lifecycle of products, the flow of materials, and the impacts on both the environment and society. This holistic perspective is crucial for understanding the complexities and interdependencies that characterize circular systems.

Circularity assessment can be conducted at different scales: nano, micro, meso, and macro. The nano scale focuses on specificities of product performance with the CE. At the micro level, the focus is assessing how circular principles are applied within a single entity, namely a process or company. Indicators at this level might include resource efficiency, waste reduction, and product lifespan extension. At the meso level, the assessment expands to encompass industrial symbiosis of industrial parks, local communities, or supply chains, examining how circular practices are integrated across multiple entities. Indicators here could measure symbiotic relationships, such as the exchange of materials and energy between businesses (Blomsma & Tennant, 2020). At the macro level, the assessment addresses regional, national, or global systems, evaluating the broader impacts of CE practices on economic, environmental, and social dimensions. Macro-level indicators might include national resource productivity, circular material use rates, and overall waste generation (Ghisellini et al., 2016).

A key challenge in circularity assessment is balancing intrinsic and consequential circularity aspects. Intrinsic circularity focuses on the inherent qualities of products and processes that contribute to circularity, such as recyclability, durability, and renewable content. Consequential circularity, on the other hand, considers the broader impacts and outcomes of circular practices, such as the reduction in environmental footprints or the creation of sustainable economic opportunities (Korhonen et al., 2018). Effective circularity assessment must integrate both perspectives to provide a comprehensive understanding of circular performance, to support decisions that enhance resource circularity whilst maintaining sustainable development.

However, without specific and systematic guidelines for selecting indicators, there is a risk of cherry-picking metrics that favourably present circularity outcomes while ignoring less conducive aspects. This selective reporting can undermine the credibility of circularity assessments and cause burden shifting which hinders progress towards genuine progress of multi-dimensional sustainability. Therefore, it is essential to establish robust frameworks and criteria for indicator selection that ensure a balanced and objective evaluation of circularity (Moraga et al., 2019).

In the bio-based sector, the concept of the bio-based value pyramid is particularly relevant for assessing circularity. As shown in Figure 1, the bio-based value pyramid prioritizes the use of biomass for the highest value-added applications first, such as food, pharmaceuticals, and fine chemicals. As biomass cascades down the pyramid, it is utilized for lower-value applications, including bioenergy and materials. This hierarchical approach maximizes the economic and environmental benefits derived

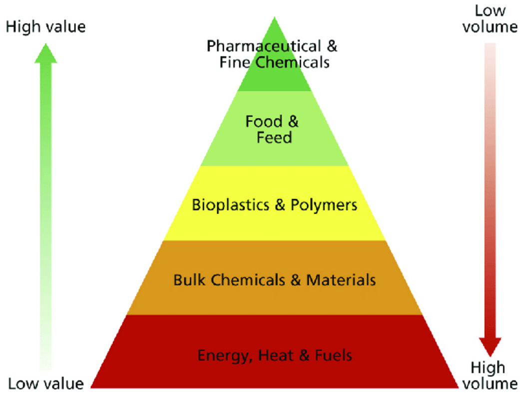

Figure 1. Biomass value pyramid (Stegmann et al., 2020).

from biomass, ensuring its efficient use at each stage (Stegmann et al., 2020). For example, a crop residue might first be used as a sustainable building material (straw bales for insulation), then as a substrate for biochemical production (chemical conversion i.e. cellulose to ethanol), and finally as a source of bioenergy (incineration). This cascading use ensures that biomass is utilized to its fullest potential, maximising its value to reduce waste and increase overall resource efficiency.

Designing for technical cycling (R activities i.e. recycling, reuse, remanufacture) and designing for degradation are two critical concepts in the bio-based sector. Designing for technical cycling involves creating products that can be easily disassembled and processed into new materials, thereby extending their lifecycle and reducing waste. Conversely, designing for degradation focuses on ensuring that products are available for biochemical mineralization by microorganisms, facilitating safe return of resources to the environment as non-toxic components. Balancing these two approaches is essential for optimizing the sustainability of bio-based products.

The unique characteristics of bio-based products, such as their renewability and potentially lower carbon footprints, present both opportunities and challenges for circularity measurement. For instance, bio-based inputs often require higher quantities to produce the same amount of product compared to fossil-based inputs, necessitating indicators that measure the efficiency of replacing non-renewable resources with renewable ones (D’Amato et al., 2017). Additionally, the ecological impacts of bio-based products, such as their effects on soil health, water quality, and biodiversity, must be integrated into circularity assessments to ensure a holistic evaluation.

Advancing circularity measurement and assessment for bio-based products requires adopting a comprehensive, systems-thinking approach that captures the unique characteristics of these materials. By integrating concepts such as the bio-based value pyramid and balancing design principles for cycling and degradation, a more holistic evaluation of circular performance can be achieved. As the bio-based sector continues to evolve, the need for tailored indicators and robust methodologies becomes increasingly critical. The upcoming discussion on the new ISO 59000 Series Standard will delve into how these emerging frameworks can be adapted to meet the specific needs of bio-based products and systems, ensuring that circularity assessments are both accurate and relevant to support decision making considering the unique dynamics of this sector.

2.1 The New ISO 59000 Series Standard

The new ISO 59000 Series Standard officially released in Spring 2024 (draft released in early 2023) provides a comprehensive framework for circularity performance measurement and assessment, designed to enhance circular performance across various sectors. This series, developed by the International Organization for Standardization (ISO), outlines methodologies for measuring resource efficiency, waste reduction, and lifecycle impacts, setting a foundation for organizations to systematically track and improve the circularity of their practices. The aim is to promote a globally consistent approach to CE principles, ensuring that businesses and industries can benchmark their performance and work towards more sustainable practices.

The ISO 59000 series includes several key standards that focus on different aspects of circularity. For example, ISO 59010 specifies the requirements for implementing and managing a CE management system, providing guidelines on how to integrate CE principles into business strategies and operations. ISO 59020 focuses on metrics and indicators, detailing how to measure circularity performance, while ISO 59004 offers complete list of CE terminology and useful guidelines for areas such as circular design, emphasizing the importance of designing products with their end-of-life in mind. Together, these standards create a robust framework that can be applied across various companies, industries, and regions.

However, the application of these standards to bio-based products requires adaptation to address their specific characteristics and lifecycle stages. Bio-based products, derived from renewable biological resources, have unique properties and supply chains that differ significantly from traditional, fossil-based products. For instance, the lifecycle of a bio-based product involves stages such as biomass cultivation, harvesting, processing, and end-of-life management, each with distinct environmental impacts and circularity challenges.

One of the main challenges in applying the ISO 59000 series to the bio-based sector is addressing the unique characteristics that differentiate bio-based systems from fossil-based ones. In bio-based systems, circular flows must consider both recycled and renewable resources. However, the ISO standards consider all recycled flows as circular as it follows ISO14021 definitions for manufacturing processes. This creates issues for bio-based products as their recycling needs to account for avoidable and unavoidable waste, and the influence of renewability on the circularity characteristics of pre-consumer waste. This broad definition can result in most bio-based products being characterized as circular, even if they do not fully meet stringent sustainability criteria. This is critical in regions such as the EU which has published legislation defining sustainability criteria for different biological resources, including Directive (EU) 2022/2448 for forest biomass.

For bio-based systems, it is crucial to ensure that renewable resources are truly sustainable, meaning their replenishment rates must meet or exceed extraction rates and they are produced using regenerative practices. This validation is necessary to prevent resource depletion and ensure long-term sustainability. Additionally, recycled flows in bio-based systems must be scrutinized to differentiate between avoidable waste, which could have been prevented with better practices, and unavoidable waste, which is an inherent part of production processes.

Another important aspect often overlooked by the ISO standards is cascading, a critical process in bio-based systems. Cascading involves the sequential use of biomass for multiple applications, maximizing the value extracted from the resource before it reaches its end-of-life. This approach is essential for enhancing resource efficiency and reducing waste in biotechnical systems, yet it is not adequately addressed in the current ISO framework.

Furthermore, bio-based feedstocks exhibit significant variability in composition, quality, and availability, influenced by factors such as geographic location, climate conditions, and agricultural and production practices. Unlike the relatively uniform industrial materials used in fossil-based systems, this variability necessitates modifications to standard measurement and assessment methodologies to accurately reflect the complexities of bio-based systems. Agricultural and production practices, including sustainable farming techniques and efficient processing methods, can be a source of this variability but must be supported as they play a crucial role in enhancing the overall sustainability of the bio-based sector and products.

Adapting the ISO 59000 series to the bio-based sector also involves addressing the end-of-life options for bio-based products. Biodegradability and compostability are critical aspects of bio-based products that are not adequately covered by traditional CE metrics. Developing specific indicators and methodologies within the ISO framework to assess the biodegradation and composting processes of bio-based products will ensure a more accurate reflection of their circularity performance.

By filling the knowledge gaps and requirements mentioned, the bio-based sector can benefit from the ISO 59000 series by adopting its principles, frameworks, and metrics, tailored to their unique needs. By incorporating sector-specific knowledge and expertise, the bio-based industry can develop more effective and accurate circularity indicators that support decision making and performance comparisons to accelerate the transition to a sustainable circular bioeconomy.

The ISO 59000 series standard provides a valuable framework for enhancing circularity across various sectors, including the bio-based sector. However, to fully leverage its potential, it is essential to adapt and expand its methodologies to address the unique characteristics and lifecycle stages of bio-based products. This adaptation process should involve multiple stakeholder groups from the bio-based industry, including producers, researchers, and policymakers, working together to refine the standards. This deliverable aims to transfer and adapt the principles of the new ISO 59020 to the bio-based sector, as this documents specifically provides a framework for performance measurement and assessment, including a list of core indicators. Therefore, its adaption ensures that the circularity indicators selected and developed are relevant, comprehensive, and capable of driving meaningful improvements in sustainability performance for the bio-based sector. By tailoring the ISO framework to the specific needs of bio-based systems, the bio-based industry can better integrate these standards into their own methodologies and certification schemes, fostering a more sustainable and resilient CE through collaboration and innovation.

2.2 Circular Indicators in Existing Certification Schemes

One of the primary objectives of BioReCer is to complement existing certification schemes by integrating comprehensive circularity indicators specifically tailored for bio-based products. Certification schemes play a crucial role in validating and promoting sustainable practices across various industries. However, detailed in Deliverable 2.2 has identified several areas where current certification schemes lack specific requirements related to circularity. It specifically highlighted the lack of quantitative circularity indicators (except carbon footprint) in existing certification approaches.

Current certification schemes often do not require companies to demonstrate that their CE initiatives result in tangible economic benefits. Additionally, there is a reluctance to do so as businesses need to allocate resources to research and develop CE strategies within their value chains. Innovating and improving circular practices require dedicated manpower and investments in research and development.

Moreover, not all certification schemes place emphasis on establishing contracts with suppliers who sell products or materials certified as circular, verifying circularity along value chains. Ensuring that entire supply chains are aligned with CE principles is fundamental for achieving comprehensive sustainability goals. Transparency of company performance and actions is another area that should be considered as part of CE certification, as they should be willing to publicly share information about their activities related to the CE to build trust and accountability and enabling consumers to make informed choices.

Due to the infancy of the CE concept in the bio-based sector, there is also a need to recognize and promote companies' efforts in raising awareness about the benefits of the CE during certification processes. Participation in awareness campaigns and educational initiatives is crucial for driving broader societal changes. Training and workforce development are essential components, with companies needing to provide specialized training activities for employees to equip them with the necessary skills for implementing circular strategies.

Ensuring that bio-based products meet the same quality and performance standards as their conventional counterparts is another critical development of certification schemes. Specifically, they should include criteria to verify that circular products do not compromise on quality. Lastly, promoting a systems-thinking approach and the analysis of material loops within processes is vital for a holistic CE strategy, meaning certification schemes must consider circularity performance during the entire product life cycle of resources.

By addressing these gaps, BioReCer aims to complement existing certification schemes, ensuring they are more comprehensive and better suited to promoting circularity in the bio-based sector. This involves developing appropriate circularity indicators for bio-based products, which can be integrated into these schemes to improve their effectiveness. The integration of new indicators can provide a more nuanced understanding of circularity, such as validating renewability, differentiating between avoidable and unavoidable waste, and accounting for cascading uses of biomass. Incorporating these advanced indicators will ensure that certification schemes not only recognize circular practices but also promote higher standards of sustainability and resource efficiency. This approach will drive significant advancements in sustainability practices, ultimately supporting the transition to a truly CE.

2.3 Alignment with the EU Taxonomy Regulation and Environmental Objectives

The EU Taxonomy Regulation is a pivotal framework that aims to guide investments towards sustainable economic activities, thereby fostering a greener and more resilient economy. The regulation sets out six environmental objectives following the Do No Significant Harm principles to assist businesses and investors in identifying and supporting activities that make substantial contributions to environmental sustainability. These six objectives are:

(1) Climate change mitigation
(2) Climate change adaptation
(3) Sustainable use and protection of water and marine resources
(4) Transition to a CE
(5) Pollution prevention and control
(6) Protection and restoration of biodiversity and ecosystems.

Each objective is crucial in addressing the various facets of environmental sustainability. Climate change mitigation focuses on reducing greenhouse gas emissions to curb global warming. Climate change adaptation involves adjusting processes, practices, and structures to minimize the damage caused by climate impacts. Sustainable use and protection of water and marine resources aim to ensure that aquatic ecosystems are preserved and utilized responsibly, maintaining their health and availability for future generations. Pollution prevention and control target the reduction of harmful pollutants released into the environment, safeguarding human health and natural ecosystems. Finally, the protection and restoration of biodiversity and ecosystems emphasize the conservation of natural habitats and the restoration of degraded ecosystems to enhance their resilience and function. However, in the context of this deliverable, the primary focus is on developing indicators that target the environmental objective of transitioning to a CE. This objective is intrinsically linked to the principles of resource efficiency, waste reduction, and the continual use of materials, which are central to the CE. By developing robust circularity indicators for bio-based products, this deliverable aims to support businesses in optimizing their resource use, minimizing waste, and enhancing the sustainability of their production processes, enabling them to showcase the resultant benefits of their efforts and investments in CE strategies.

While the direct emphasis is on CE indicators, the development of these indicators indirectly addresses some of the other environmental objectives outlined in the EU Taxonomy Regulation. For instance, improved circular practices can contribute to climate change mitigation by reducing emissions associated with resource extraction and waste management. Additionally, promoting the use of renewable bio-based resources can support the protection of biodiversity and ecosystems by reducing reliance on non-renewable resources that often result in habitat destruction and biodiversity loss.

Sustainability indicators that cover a broader range of environmental objectives are comprehensively addressed in Deliverable 2.2. To avoid overlap and ensure a focused approach, this deliverable does not develop indicators targeting all six environmental objectives of the EU Taxonomy Regulation. Instead, it emphasizes alignment with the EU taxonomy by concentrating on CE indicators, ensuring that the developed indicators are consistent with the overarching regulatory framework while complementing the broader sustainability assessments covered in Deliverable 2.2. This strategic focus ensures that the circularity indicators are not only relevant and impactful but also integrated within the larger context of environmental sustainability as outlined by the EU Taxonomy Regulation.

2.4 Bio-based Sector Specificities

The bio-based sector is simply characterized by its reliance on renewable biological resources, distinguishing it from sectors that predominantly use non-renewable feedstocks. However, the BioRecer projects also aims to valorise alternative, non-conventional feedstocks and bio-based residues, to generate products that can be utilised, cascaded, cycled in both biological and technical cycles. Therefore, assessment methods developed, and indicators selected must encompass all potential properties, uses, and end-of-life scenarios of bioresources as the CE transition advances.

These biological resources can be derived from plants, animals, and microorganisms and are used to produce a diverse array of products, including food, feed, bio-based materials, chemicals, and bioenergy. The fundamental principle of the bio-based sector is the sustainable production and use of these renewable resources to create products that integrate into both biological and technical cycles – as depicted in Figure 2.

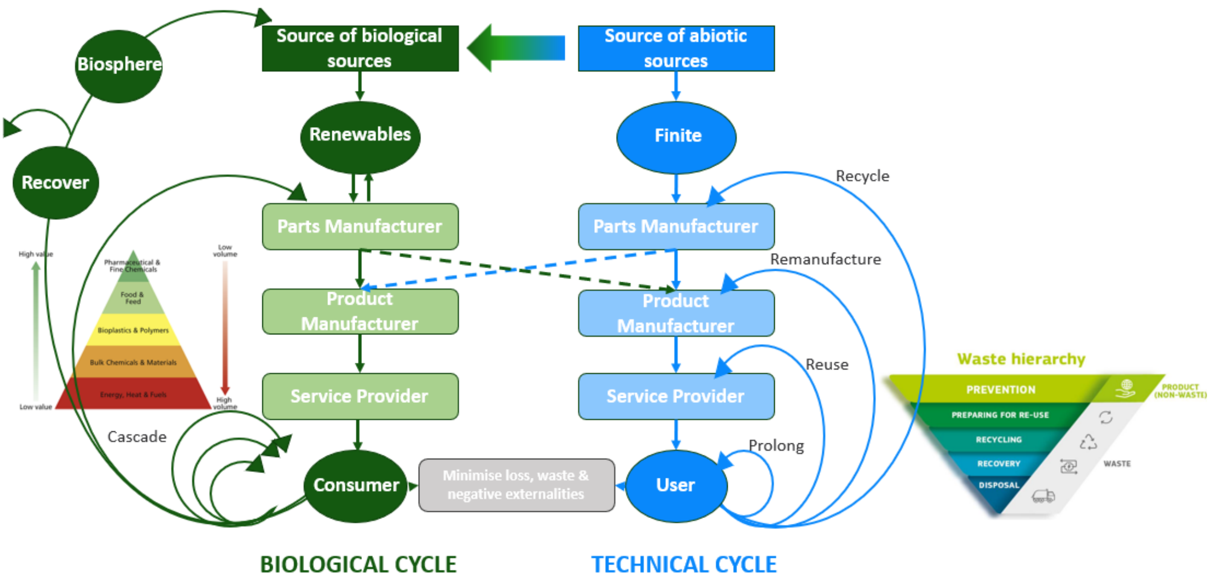

Figure 2: CE concept integrating technical and biological cycles.

The biological cycle is a key component of the bio-based sector. In this cycle, renewable resources undergo natural processes such as growth, decay, and nutrient recycling. Products derived from biological sources can biodegrade and return nutrients to the biosphere, thus supporting the growth of new biological resources. This regenerative aspect is unique to the biological cycle and is critical for maintaining the sustainability of bio-based products. For example, agricultural residues can be composted to produce organic fertilizer, which enriches the soil and promotes the growth of new crops. Similarly, bio-based products like biodegradable plastics can decompose in composting facilities, returning valuable nutrients to the environment and reducing waste.

In addition to the biological cycle, bio-based products can also enter the technical cycle. This occurs when biological resources are mixed with abiotic or fossil-based materials, resulting in products that are not biodegradable and must be managed within the technical cycle. The technical cycle focuses on maintaining the value of products, components, and materials through strategies such as recycling, remanufacturing, reuse, and prolonging the life of products. For instance, a bio-based polymer mixed with fossil-based additives may not be biodegradable but can be recycled and used to manufacture new products. In this scenario, the product is kept in use for as long as possible, minimizing waste and maximizing resource efficiency.

Characterization of bio-residues and bio-wastes is also crucial. Current approaches often consider the utilization of waste as inherently circular, which can be overly simplistic. Not all waste is equal, and effective circularity requires a nuanced understanding of the different types of waste and their potential uses. Prevention of waste, efficient valorisation, and the management of upstream and downstream linkages are essential for understanding true circularity of resources in the bio-based sector.

The bio-based sector faces several challenges in achieving circularity. One of the primary challenges is accurately monitoring and assessing the circularity of bio-based products. The dynamic and regenerative nature of biological cycles complicates the development of standard metrics that can capture the complete and/or multiple lifecycles and impact of these products.

Another significant challenge is the variability in the quality and availability of biomass. Biological resources can vary widely in quality due to factors such as seasonal changes, geographic differences, and varying agricultural practices. This variability can affect the consistency and performance of bio-based products, and therefore value, also posing a challenge for industries that require uniformity and reliability of materials.

Economic barriers also play a role. Transitioning from fossil-based to bio-based systems involves significant initial costs, including investments in new technologies, processes, and infrastructure. Therefore, there is potential for the bio-based alternative to be more costly than the conventional or fossil-based product. Additionally, the market for bio-based products is still developing, and there may be limited consumer awareness and acceptance, which can impact demand and economic viability. Circularity indicators are able to provide a robust evidence base for investor and consumer education, helping to alleviate the barriers for uptake and replication.

Technically, the processes involved in converting biomass into valuable products can be complex. Biorefining, which aims to maximize the value extracted from biomass by separating it into various components for different applications, requires sophisticated technologies and processes. This complexity can lead to higher costs and technical challenges that need to be addressed to make renewable, residue, or alternative feedstock derived products competitive with their conventional or fossil-based counterparts.

Given these specificities and challenges, there is a critical need for circular indicators that can effectively measure and manage the circularity of bio-based products. These indicators must capture the unique aspects of both the biological and technical cycles, providing a comprehensive assessment of intrinsic circularity of resource flows through waste reduction and resource utilisation efficiency. Effective circular indicators can help monitor the renewability of resources, the efficiency of cascading use, and the closing of nutrient cycles to understand the performance of CE strategies. They also need to address the variability in biomass quality and availability, economic feasibility, and technical complexities of biorefining processes. By developing and implementing robust circular indicators, the bio-based sector can better demonstrate its sustainability credentials, enhance resource management, and drive the transition to a more CE. These indicators will enable stakeholders to make informed decisions, optimize production processes, and improve the overall sustainability of bio-based products.

2.5 Available Circular Indicators & Applicability to Bio-based Products

A semi-systematic literature review (completed 2023) has been conducted to identify and analyse existing circular indicators and their applicability to bio-based products. Both scientific and grey literature were considered during the review process, as D2.2 highlighted the lack of circularity indicators in published reports. This analysis covers both product-based (Table 1) and process-based (Table 2) indicators, as well as assessing their adequacy and recommending areas for improvement (Table 3).

Table 1 provides a comprehensive list of micro-level indicators that are currently used to measure circularity. These indicators primarily focus on the recycling, reuse, resource efficiency, and utility aspects of products and companies. Examples include the Material Circularity Indicator (MCI), Recycling Indicator Set, and Reuse Potential Indicator (RPI).

Table 1: Micro-level Indicators

Indicator Name	Reference	Description	Main Focus
Biomass Utilization Efficiency (BUE)	(Iffland et al., 2015)	Measures the percentage of initial biomass ending up in the end product.	Resource Efficiency
Biomass Utilization Factor (BUF)	(vom Berg et al., 2022)	Quantifies the extent and frequency of biomass utilization in a bio-based product value chain.	Resource Efficiency and Cascading Use
Bioresource Utilization Index	(Vamza et al., 2021)	Quantifies resource efficiency by considering raw material, product, by-products, and waste.	Resource Efficiency
Cascade Use Indicators	(Hildebrandt et al., 2017)	Quantifies material recycling and energy recovery efficiency in bio-based polymers.	Cascading Use
Cascading Factor	(Mantau, 2015)	Calculates the single or multiple use of a resource in a production system.	Cascading Use
Circ(T)	(Pauliuk et al., 2017)	Measures the cumulative mass of a material over a certain time interval in terms of an ideal reference case.	Resource Efficiency and Utility
CE Benefit Indicators (RBR and RCBR)	(Huysveld et al., 2019)	Assess the environmental benefits of recycling, considering lifetime differences between products made from recycled and virgin materials.	Recycling, Environmental Impact
CE Index (CEI)	(Di Maio et al., 2017a)	Ratio of material value from recycled products to the material value needed for reproducing the product.	Recycling
CE Performance Indicator (CPI)	(Huysman et al., 2017)	Assesses circularity performance considering resource consumption and environmental impact.	Recycling, Environmental Impact
CE Toolkit (CET)	(Evans & Bocken, 2014)	Considers biodegradable materials and use of toxic materials in products.	Regeneration and Hazardous Substances
Circularity Index (CI)	(Cullen, 2017)	Measures the mass of recovered material with respect to total material demand.	Recycling
Circularity Indicators	(Ladu & Morone, 2021)	Integrated assessment tool for sustainability assessment of bio-based products, including circularity aspects.	Multiple Criteria (Sustainability)
Circularity Measurement	(Garza-Reyes et	Includes renewable material input and energy intensity.	Renewable Resources and

Toolkit (CMT)	al., 2019)		Energy
Circularity of Material Quality (QC)	(Steinmann et al., 2019)	Focuses on the quality of materials, considering the energy required for processing and possible mixing with primary materials.	Quality
Combination Matrix (CM)	(Figge et al., 2018)	Combines circularity metrics with longevity indicators to evaluate the overall circularity and utility of materials.	Recycling and Utility
Global Resource Indicator (GRI)	(Adibi et al., 2017)	Integrates scarcity and criticality of resources used, including geopolitical availability and recyclability.	Resource Efficiency
Hybridised Sustainability Indicators	(Lokesh et al., 2020)	Combines green chemistry and resource circularity principles with LCA indicators.	Resource Efficiency, Hazardous Substances
In-use Occupation Indicator	(Moraga et al., 2019)	Considers sequential products, accounting for losses at each phase and the strategies used to increase product lifetime.	Utility
Longevity Indicator (LI)	(Franklin-Johnson et al., 2016)	Measures the durability of a product by considering its initial lifetime, refurbished lifetime, and recycled lifetime.	Utility
Material Circularity Indicator (MCI - update 2019)	(Ellen MacArthur Foundation, 2019)	Includes share of biological materials as input and composting and energy recovery of biological materials at the end of life.	Recycling and Biological Content
Material Circularity Indicator (MCI)	(Ellen MacArthur Foundation, 2015)	Assesses the share of recycled material as input and the fraction going to recycling after use.	Recycling
Modified MCI	(Razza et al., 2020)	Modification of MCI to incorporate bio-based content and organic recycling.	Recycling and Biological Content
Product Circularity Indicator (PCI)	(Bracquené et al., 2020)	Includes efficiency of the production and recycling processes, considering material losses.	Resource Efficiency and Utility
Product-Level Circularity Metric (PLCM)	(Linder et al., 2017)	Measures the fraction of the economic value coming from recirculated parts.	Recycling and Resource Efficiency

Recycling Indicator Set	(Nelen et al., 2014)	Measures the amount of recycled input used and the extent to which a product gets recycled at the end of its life.	Recycling
Recycling Indices (RI)	(van Schaik & Markus A. Reuter, 2016)	Includes Product-RI (total recycling and recovery rate of a product) and Material-RI (recycling rate of individual materials or elements of a product).	Recycling
Reuse Potential Indicator (RPI)	(Park & Chertow, 2014)	Assesses the intrinsic value for reuse that a material has according to the current available technologies.	Recycling
Sustainable Circular Index (SCI)	(Azevedo et al., 2017)	Combines sustainability indicators with circularity indicators to provide a comprehensive assessment.	Recycling and Resource Efficiency
Value-based Resource Efficiency (VRE)	(Di Maio et al., 2017b)	Uses the monetary value of resources to calculate resource efficiency.	Resource Efficiency

Many indicators presented in Table 1 such as the Recycling Indicator Set, CE Index (CEI), and Material Circularity Indicator (MCI) emphasize recycling. These indicators measure the extent to which materials are reused and recycled at the end of their life cycle, reflecting the CE's principle of material recirculation. However, they often overlook other important aspects like the renewable content and the sustainability of the resource extraction process.

Indicators such as the Biomass Utilization Efficiency (BUE) and Value-based Resource Efficiency (VRE) assess how efficiently resources are used in production processes. These indicators are crucial for bio-based products as they highlight the efficient use of biomass and other resources. However, they may not fully capture the cascading use and multiple stages of resource utilization specific to bio-based products.

Some indicators like the Longevity Indicator (LI) and Circularity of Material Quality (QC) focus on the utility and quality of materials. These indicators measure the durability and the quality maintenance of products through their lifecycle. For bio-based products, this is particularly important as it can address the variability in biomass quality and the need for high-quality end products.

The CE Benefit Indicators (RBR and RCBR) and CE Performance Indicator (CPI) integrate environmental and social impacts into the assessment of circularity. While these indicators are relevant, they often require more robust data and methodologies to accurately reflect the unique environmental and social benefits of bio-based products.

Table 2 lists process-based indicators, predominantly derived from the ISO 59020 standard, which measure circularity within specific processes for resource flow X. These indicators cover aspects such as reused and recycled content, renewable content, product lifetime, energy and water use, and economic value.

Table 2: Circularity Indicators of ISO 59020

Indicator Name	Description	Main Focus
Average Reused Content of an Inflow (X)	Measures the average fraction of an input material resource (X) that is reused.	Reused Content
Average Recycled Content of an Inflow (X)	Represents the fraction of input resources confirmed as recycled material.	Recycled Content
Average Renewable Content of an Inflow (X)	Measures the fraction of a resource inflow (X) that meets specified conditions for renewable material.	Renewable Content
Average Lifetime of Product or Material Relative to Industry Average	Identifies the degree to which a resource outflow retains its value over time compared to industry average.	Product Lifetime
Percent Actual Reused Products and Components Derived from Outflow (X)	Calculates the fraction of outflow (X) recovered for reuse in production, maintenance, or repair.	Reused Products
Percent Actual Recycled Material Derived from Outflow (X)	Represents the effective level of recovering materials from resource outflows through collection and recycling.	Recycled Material
Percent Actual Recirculation of Outflow (X) in the Biological Cycle	Measures the fraction of outflow (X) recirculated at end of life for safe return to the biosphere (biodegradation).	Biological Recirculation
Average Percent of Energy Consumed that is Renewable Energy	Represents the fraction of consumed energy that qualifies as renewable energy.	Renewable Energy
Percent Energy Recovered from Residual, Non-renewable and Non-recoverable Resource Outflows	Per cent energy recovered from residual, non-renewable and non-recoverable resource outflows	Energy Recovery
Energy Intensity	The amount of energy used to produce a given level of output or activity	Energy Intensity

Percent Water Withdrawal from Inflow Circular Sources	Expresses the percentage of annual water demand derived from circular sources.	Circular Water Sources
Percent Water Discharged in Accordance with Quality Requirements	Measures the percentage of water discharged meeting the quality level required for reuse or return to source.	Water Quality
Ratio (On-site or Internal) Water Reuse or Recirculation	Measures the circularity of water within a facility, comparing total water use to the amount withdrawn from sources.	Water Reuse
Water Intensity	The amount of water used to produce a given level of output or activity	Water Intensity
Nutrient Extraction from Discharged Water	Extraction of nutrients from water before discharge	Nutrient Extraction
Percent Designed Reusability Rate of the Outflow	Reusability based on design	Reusability
Percent Designed Recyclability Rate of the Outflow	Recyclability based on design	Recyclability
Material Productivity	Ratio of an organization’s revenue to total linear (non-circular) resource inflows.	Material Productivity
Resource Intensity Index	Ratio of the change rate of resource consumption to the change rate of GDP over time, indicating economic growth vs. resource use.	Resource Intensity
Net Value Added	Value of a product minus negative economic factor costs	Economic Value
Value per Mass	Value per unit mass of resource	Resource Value
Resource Productivity	Ratio of GDP and DMC or RMC	Resource Productivity
Genuine Process Indicator	Measures GDP after removing negative impact costs	Genuine Process Indicator

Indicators included in Table 2 such as the Average Reused Content of an Inflow (X) and Average Recycled Content of an Inflow (X) measure the proportion of reused and recycled materials in the production process. These indicators are directly applicable to bio-based products, emphasizing the importance of integrating recycled content into new bio-based products.

The Average Renewable Content of an Inflow (X) is particularly relevant for bio-based products, as it measures the fraction of resources that are renewable. This aligns with the bio-based sector's focus on sustainable and renewable resource utilization.

Indicators such as Average Percent of Energy Consumed that is Renewable Energy and Percent Water Withdrawal from Inflow Circular Sources assess the efficiency and sustainability of energy and water use in processes. These indicators are critical for bio-based products, which often involve energy-intensive and water-intensive processes.
The Net Value Added and Resource Productivity indicators evaluate the economic benefits derived from circular processes. These indicators help in understanding the economic viability of bio-based products and their contribution to the CE.

Table 3 evaluates the adequacy of available circular indicators and identifies gaps, providing recommendations for further development.

Table 3: Adequacy of available circular indicators and recommendations

Value Chain	Aspect	Indicator objectives	Indicators availability	Indicator Gap
Resource extraction	Finite vs Renewable Resources	Increase use of renewable resources, replacing finite resources	Indicators measuring the renewable content of a product exist	Renewable content is commonly considered circular
		Sustainable production of renewable resources validation	Not covered	To assign circularity, the verification of sustainably produced renewable resource is needed
		Resource renewability validation	Limited indicators in scientific literature but partially covered by the definitions and/or criteria for some ISO59020 indicators	Use of biotic resources within sustainable limits, ecosystem production capacity remains stable over time
		Savings in finite resources considering scarcity & criticality	Few indicators exist	-
	Virgin vs Secondary Resources	Increase use of secondary resources, replacing virgin resources	Indicators measuring the recycled, reused, cascaded, etc. content of a product exist	Often secondary resources refer to utilisation of residues and/or waste; not all waste and residues are equal; to assign circularity in secondary resources further considerations are required, including a differentiation between pre-consumer and post-consumer resources
		Reduction of residues, losses & waste due to their	Indicators exist	Waste, losses and residues prevention should be prioritised

		further utilization in a new value chain		over reduction due to further valorisation
Treatment of feedstock for product generation	Efficient use of resources	Actual value of the utilised resource achieved vs the maximum value of the utilised resource	Most of the available indicators focus on the utilisation of the resource itself (biomass utilisation)	The bio-based pyramid is often neglected in the calculation of circular indicators; also, resources can be utilised either for their mass or for their substances however, no such consideration is made in available indicators
		Production or Technical efficiency	Indicators focusing on resource / energy / water / chemicals used per product generated exist	Benchmarking is required
		Waste-related efficiency	Indicators focusing on waste/losses generated per input required or per product generated exist	The fate of generated or redirected resource is needed
		Resource productivity	Indicators such as economic output per input required exist	Benchmarking is required
		Emission intensity	Indicators such as emissions per input required exist	Benchmarking is required
	Security	Production security	Not adequately addressed	Indicators should consider: stability of production / seasonality, quality of product according to industry specifications, human-health & environmental safety, technology maturity, product desirability
Technical cycle	Technical recirculation	Refers to reuse, remanufacture, recycle,	Most of the available indicators focus on this	Changes in quality requires further attention; also differentiation is

		recover, etc.	aspect	required between recirculated content of the product and recirculating potential of the product
Biological cycle	Biological recirculation (Cascading)	Maintaining the (resource, material, product) value for as long as possible in as high quality as possible	Few cascading indicators but quality degradation & appropriate fit are missing	This may include: favouring the highest value-added use of biomass (bio-based value pyramid), making use of the entire feedstock including all co-products and by-products as part of cascading, and the sequential use of biomass
Throughout	Resource stewardship	Closing, slowing, and narrowing resource flows to ensure resource availability	A few indicators exist measuring directly narrowing objectives	Direct indicators measuring the degree narrowing resource flows are required to connect local industries and promote symbiosis
	Accumulation of hazardous substances	Legislative restriction and thresholds for hazardous substances for the ingredients used in production, measurement and comparison to thresholds	Not taken into consideration by circularity metrics (partially covered by some LCA impact categories)	Risk assessments for circular products are gaining momentum but there are no mainstreamed indicators to be used; data provision regarding potential presence of hazardous substances must be disclosed, enabling an indication of potential risk and how this influences circularity (qualitative indicators)
Return to biosphere	Regeneration of natural systems	Safe return of used resources to the biosphere as the final EoL	Requires further attention (only mentioned as a consideration in ISO59020)	Biodegradability, compostability, eco-toxicity as a result of biodegradation, nutrients returned to the place and at a rate at which ecosystems absorb them

Environmental value & impacts	Biotic resource use impacts the quantity and quality of ecosystems, natural capital, biodiversity	Pollution prevention and control, Protection and restoration of biodiversity and ecosystems	Requires advancements	-
	Land-use interventions	Land occupation, Land transformation	Indicators exist	-
	Carbon emissions (biogenic sources are often assumed to be "carbon neutral")	Biotic resources should be harvested at a rate below the rate of sequestration to maintain the flux of carbon through the sink over time, validating biomass 'carbon neutrality' credentials	Indicators exist but changes may be required for validating carbon neutrality	-
Economic value & impacts		Consideration of value or price of products or materials, monetary representation of resource flows, economic feasibility, and economic gains, eco-efficiency (the ratio of environmental burden to the economic value)	Some methods to monetise environmental & social impacts are available but they can be complex or have limited accuracy/reliability	-
Social value & impacts		Workers well-being, equity, job creation opportunity, exposure of employees to hazardous materials, level of customer satisfaction	Indicators exist but this aspect is often neglected	-

Based on the analysis of Table 3, indicators exist to measure the renewable content of products, but there is a lack of indicators validating the sustainable production of these renewable resources. Future development should focus on creating indicators that assess the sustainability of resource extraction and production processes.

While indicators for efficient resource use exist, they often do not differentiate between types of residues and wastes. A more nuanced approach is required to accurately assess the circularity of secondary resources, such as detailing the properties required for the characterisation of wastes (pre- and post-consumer).

Indicators focusing on technical efficiency, such as energy and water use per product generated, are available but need benchmarking for accurate and comparative assessments. Additionally, waste-related efficiency indicators need to consider the fate of generated or redirected resources.

Indicators measuring technical recirculation are well-developed, but there is a need for more indicators that assess the quality and fit of cascading use in biological cycles. This includes favouring high-value-added uses of biomass and ensuring the entire feedstock is utilized efficiently.

There are indicators measuring the broader environmental, economic and social impacts of bio-based products, including life cycle assessment (LCA) and carbon footprint, life cycle costing, and social LCA impact indicators respectively. Further developments that address and incorporate pollution prevention, biodiversity protection, and social equity aspects are required for a comprehensive assessment of bio-based circularity value creation. However, these indicators do not investigate the intrinsic circularity of resources and many of these dimensions are explored further in D2.2, so were considered outside the focus of this study.

3 Circular Indicators Selection Methodology for Bio-based Products

As shown in Table 1 and 2 there is now an abundance of CE indicators that have been developed by scientific literature, and more recently by international standardisation bodies. However, as described in Table 3 there are many gaps identified that potentially limit the applicability and utility of these metrics for the assessment of bio-based products, and the holistic assessment of bio-based systems CE objectives.

In Deliverable 2.2, a comprehensive set of circularity criteria was identified to guide companies towards more sustainable and circular business practices. These criteria are organized under four main pillars: Economic, Environmental, Environmental and Economic, and Social. Each criterion is associated with specific requirements that companies must fulfil to demonstrate their commitment to CE principles.

Under the Economic pillar, the criteria emphasize systems thinking and business model innovation. Companies are encouraged to promote strategies of industrial symbiosis by collaborating with other organizations to optimize resource use. They must also show that their circular business practices lead to economic benefits, support innovation and procurement of circular products, and maintain transparency in their circularity efforts. These criteria aim to ensure that companies are not only adopting circular strategies but are also creating value and fostering innovation within their value chains.

The Environmental and Economic pillar focuses on the elimination of waste and pollution, the availability of resources, and value creation. Companies are required to consider end-of-life treatments for waste valorisation, monitor the environmental impacts of their circular strategies, and promote the substitution of virgin materials with secondary raw materials. Additionally, they must implement practices that contribute to the resilience and regeneration of natural capital, such as resource recovery and water reclamation. This pillar underscores the importance of maintaining the highest value and utility of resources while ensuring that circular practices result in tangible environmental and economic benefits.

The Social pillar highlights the importance of social procurement, communication, and education programs. Companies must engage in awareness campaigns, provide training for workers on circular technologies and strategies, and create employment opportunities aligned with the needs of the CE. These criteria ensure that the transition to a CE is inclusive and benefits the broader society by creating jobs and building skills.

While these criteria provide a robust framework for promoting CE practices, they are relatively generic and broad in scope. This broadness ensures that the criteria are applicable to a wide range of companies, regardless of their position in the supply chain, the type of feedstock they use, or the products they generate. Additionally, the approach followed by Deliverable 2.2 mixes intrinsic circularity with consequential circularity, addressing both the internal mechanics of circular practices and their broader sustainability impacts. To effectively select a robust set of product-based circularity indicators for bio-based system assessments, it is necessary to develop some prerequisite conditions that are more specific to intrinsic circularity analysis. These conditions help to translate the broad requirements of the CE summarised in D2.2 into measurable and practical indicators that can be directly applied to bio-based products and processes. By refining them into detailed indicators, the circularity performance of bio-based systems can be better assessed, ensuring alignment with the overarching requirements while achieving specific, quantifiable outcomes in terms of resource efficiency, waste reduction, and sustainability impacts.

3.1 Prerequisites for Indicator Selection

Some prerequisites for indicator selection must be developed as part of the methodology, providing a framework to ensure that the indicators provided in this work are: 1) aligned with standardised circularity assessments, 2) maximise analysis of bio-based sector CE objectives, and 3) appropriate for the assessment of bio-based products within technical and biological cycles.

Selecting indicators aligned with standardized assessments is crucial for several reasons. It ensures consistency and comparability, enabling stakeholders to benchmark performance accurately and identify best practices. Additionally, alignment with standardized assessments enhances credibility and acceptance among policymakers, investors, and other stakeholders, as these indicators are recognized and validated by authoritative bodies. This credibility is critical for driving policy decisions, attracting investments, and gaining stakeholder trust. Standardized indicators also support transparency and accountability by providing clear, measurable, and universally understood metrics. This transparency is vital for reporting and communicating the circularity performance of products and processes, fostering trust and collaboration within the value chain. Moreover, using standardized indicators helps streamline regulatory compliance and reporting requirements, reducing the burden on organizations to develop and justify their metrics independently. Standardised indicators will be excluded in case they do not reflect the scale of the assessment for this deliverable (i.e. nano and micro scale are appropriate to measure and assess circularity of bio-based products).

In cases where standardized circularity indicators do not effectively cover the bio-based sector CE objectives, the inclusion of additional indicators is justified. Appropriate indicators available in the literature will be selected to ensure comprehensive assessment. The bio-based sector has unique characteristics and challenges that may not be fully addressed by generalized circularity indicators. Therefore, it is essential to consider the specific CE objectives of the bio-based sector to accurately measure and promote resource efficiency and circularity within this context. Including tailored indicators ensures that all relevant aspects of bio-based products are assessed, leading to more effective and targeted strategies for achieving CE goals.

Ensuring that indicators are appropriate for the assessment of bio-based products within both technical and biological cycles, is crucial because bio-based products designed for each cycle have distinct characteristics and needs. Indicators applicable to technical cycles focus on aspects such as reuse, remanufacturing, repurposing, and recycling while those for biological cycles emphasize cascading, biodegradability, compostability, and safe return to the environment. By selecting indicators tailored to each cycle, we can accurately assess and promote the specific CE objectives relevant to the diverse pathways bio-based products follow, ensuring comprehensive and effective evaluations.

3.1.1 Standardised Indicators according to ISO 59000 series

The standardised circularity indicators of the ISO 59020 (Table 2) stress the importance of assessing a product's circularity across all life cycle phases along the value chain. They differentiate between indicators targeting: 1) material inputs used to generate the product; 2) circular production of the product; 3) use phase of the product; 4) product's end-of-life (EoL); and 5) economic circularity benefits.

Three ***material input*** indicators are identified: the fraction of input that is reused (Average reused content of an inflow), recycled (Average recycled content of an inflow), and renewable (Average renewable content of an inflow). Combined, these three indicators can measure the circular input of a product. As the standardized circularity indicators of the ISO have been developed to be applicable both to products and processes/companies, this deliverable defines the material inputs related specifically to the product (i.e. product-function materials). This means that materials required for the operation of processes (i.e. process-function materials), which do not form part of the product, are not considered in this first category of indicators. Instead, they are included in the circular production indicators category.

Additionally, the transferability of these indicators to bio-based products requires clarification as the main material input (feedstock) is often of biological origin and typically assumed to be renewable. This overlap means that some recycled or reused inflows might also be renewable, potentially leading to double counting. Therefore, the Average renewable content of an inflow indicator is slightly modified in this deliverable to Average **virgin** renewable content of an inflow indicator. Additionally, the Average recycled content of an inflow indicator is split into two indicators: i) Average **pre-consumer** recycled content of an inflow, and ii) Average **post-consumer** recycled content of an inflow. The differentiation between pre- and post-consumer recycled content is important for accurately assessing the source and impact of the recycled materials in a product's life cycle.

- **Pre-consumer recycled content** refers to inputs that have been recycled from manufacturing waste/residues before they reach the consumer. This includes scraps, trimmings, and other by-products generated during the production process.
- **Post-consumer recycled content** refers to materials that have been used and discarded by consumers, then collected, processed, and recycled into new products.

Using these four modified ISO-based indicators, the product's circular content of inflows can be measured, considering that inputs from virgin non-renewable sources are linear and do not contribute to the product's circularity value.

Regarding ***circular production***, ISO defines three energy-related indicators (Average Percent of Energy Consumed that is Renewable Energy; Percent Energy Recovered from Residual, Non-renewable and Non-recoverable Resource Outflows; Energy Intensity) and five water-related indicators (Percent Water Withdrawal from Inflow Circular Sources; Percent Water Discharged in Accordance with Quality Requirements; Ratio of On-site or Internal Water Reuse or Recirculation; Water Intensity; Nutrient Extraction from Discharged Water). The Nutrient extraction from discharged water indicator is a case-specific indicator related to resource recovery from wastewater facilities, so it is not applicable to all bio-based industries.

For the energy-related indicators, the renewable and recovered content represent the total circular energy content. Since this deliverable focuses on product-specific indicators, the energy used/consumed refers to the process train associated with the specific product, not the total energy used/consumed by the entire company, as different products may have different process trains. Additionally, for Energy Intensity, an additional indicator can be added to compare the energy intensity of the current product to that of a conventional counterpart following best available techniques. This comparison can highlight potential energy demand reduction.

For the water-related indicators, circular water sources include externally reused or recycled water and naturally renewable sources such as freshwater or non-freshwater that is sustainably managed. Internal recirculation refers to the reuse of water within the same facility or process train. This internal recirculation is not included in the calculation of circular water sources, as it does not involve withdrawing additional water from external sources. Additionally, for Water Intensity, an additional indicator can be added to compare the water intensity of the current product to that of a conventional counterpart following best available techniques. This comparison can highlight potential water demand minimization.

As process-function materials are excluded from the material inputs indicator category, circularity indicators representing them are included in the circular production indicator category. Examples of process-function materials include chemicals required for process operation (related to the product) that are not intended to form part of the product. Therefore, three indicators are included: circular process-function materials input (considering reused, recycled, renewable materials), process-function materials intensity, and process-function materials minimization (following the same approach as energy- and water-related indicators). Depending on the application, the process-function material indicators can be calculated individually for each material or combined.

Finally, as this deliverable follows a product-based approach, production process outputs excluding the generated product need to be considered in this indicator category as well. This relates to by-products, residues, and waste generated during the production process that are either valorised or not, excluding wastewater, which is considered in the water-related indicators. Two standardised indicators obtained from the use phase and EoL of the product are included for this purpose: i) Percent Actual Reused Products and Components Derived from Outflow, and ii) Percent Actual Recycled Material Derived from Outflow.

Regarding the ***use phase of the product***, ISO defines three circularity indicators: Average Lifetime of Product or Material Relative to Industry Average, Percent Actual Reused Products and Components Derived from Outflow, Percent Designed Reusability Rate of the Outflow. Here, to differentiate between the indicators referred to the products and the indicators referred to the by-products, the word "product" is used instead of "outflow". The first indicator, focusing on lifetime extension, is more applicable to durable products, as these products can have varying lifetimes during use, aiming to combat planned obsolescence. Products that are designed to be consumed cannot have an extended lifetime during their use phase. In this case, extension refers to their storage (expiration date) and not to their use phase. As extended expiration dates often require the use of chemicals, such as additives and preservatives, which may result in impacts not related to intrinsic circularity, this indicator is only considered for durable products. Similarly, a product that is being consumed cannot be reused (including refurbished, remanufactured, etc.) so again, the two indicators related to product's reusability are applicable to durable products.

Regarding the ***product's EoL***, ISO defines three circularity indicators: Percent Actual Recycled Material Derived from Product, Percent Designed Recyclability Rate of the Product, and Percent Actual Recirculation of Product in the Biological Cycle. At the EoL, a

product should be either mechanically or chemically recycled to start a new technical cycle. If this is not possible due to the nature of the product, then it should be either compostable or biodegradable to close the loop in the biological cycle by safely and effectively returning components/resources to the biosphere. The last resort to maintain value and circularity is for the product to be used for energy recovery, which is already considered in the energy-related indicators. If none of the above is feasible or actually occurring, then the EoL of the product is linear.
Regarding the ***economic circularity benefits***, ISO defines six circularity indicators: Material Productivity, Resource Intensity Index, Net Value Added, Value per Mass, Resource Productivity, and Genuine Process Indicator. Among these indicators, Resource Intensity Index, Resource Productivity, and Genuine Process Indicator are macro-level indicators, while Material Productivity focuses on the total economic activities of a company or organization. Therefore, these indicators are excluded from the present deliverable, and only the Net Value Added and Value per Mass economic indicators are considered, representing product-level circularity indicators.

3.1.2 Bio-based Circularity Objectives

As discussed in Table 3, there are many potential CE objectives of bio-based product value chains. However, many indicators in Tables 1 and 2 are not able to account for the circular characteristics of bio-based products simultaneously. Therefore, bio-based circularity objectives have been taken from (Vural Gursel et al., 2023) to ensure that the selected indicators are able to consider the prioritised CE objectives of bio-based products. The bio-based circularity objectives include the following:

1. Increase share of renewable resources (in primary resources used)
2. Use resources efficiently (including use of residues and wastes)
3. Ensure regeneration of natural systems
4. Increase recirculation of materials
5. Maximise the utility of products (include cascading use)
6. Minimise risk of accumulation of hazardous substances
7. Positive effect on i) environmental protection (e.g. pollutants, GHG emissions), ii) economic viability (e.g. value added), iii) social equity (e.g. jobs creation, social wellbeing).

The first five objectives reflect intrinsic circularity aspects, while the remaining two concerns consequential circularity (Renfrew et al., 2024). Although two economic circularity indicators have been identified in ISO 59020 and reported in the previous section, this objective is not further analysed in this deliverable (detailed explanation of economic assessments can be found in deliverable D2.2). Regarding the rest, objective number 3, objective number 5, and objective number 6 are not adequately addressed by the standardized indicators of the previous section.

To include considerations regarding the **regeneration of natural systems**, the material inputs indicators of Average Virgin Renewable Content of an Inflow and Average (Pre- and Post-consumer) Recycled Content of an Inflow can be slightly modified in their characterization. For the Average Virgin Renewable Content of an Inflow indicator, the default assumption that biological resources are renewable is not adequate for reporting and considering them in the calculation of circular inputs. Renewability refers to the ability of a resource to be replenished or regenerated at a rate that is equal to or greater than the rate at which it is extracted or consumed. For a resource to be considered renewable, its natural replenishment rate must meet or exceed the abstraction rate, ensuring that its availability is sustained over time. This balance allows the resource to be used continuously without leading to depletion and any negative environmental impacts that result from this. Therefore, to consider an inflow as renewable, its renewability should be verified either through available certification schemes and/or legislation or using documented evidence of sustainable management practices that demonstrate the resource's replenishment rate meets or exceeds its extraction rate. The same characterization rule applies to the Average Pre-consumer Recycled Content of an Inflow in the case it is of biological/biotic origin, as pre-consumer recycled materials have not yet fulfilled their function.

Regarding the better inclusion of **cascading use** in the standardized indicators of the previous section, a clearer understanding of the concept is required. According to Stegmann et al. (2020), there are three different interpretations of the term: 1) prioritizing the use of biomass for the highest value-added applications, 2) utilizing the entire feedstock along with all co-products and by-products (e.g. through co-production), and 3) the successive/sequential use of biomass. Four key indicators are identified in the literature (Table 1) reflecting the cascading concept: the Biomass Utilization Factor (BUF), Cascade Use Indicators, the Bioresource Utilization Index (Buind), and the Cascading Factor. The Biomass Utilization Factor (BUF), as outlined by vom Berg et al. (2022), quantifies the extent and frequency of biomass utilization by considering the entire feedstock, including all co-products and by-products, ensuring comprehensive resource efficiency. The Cascade Use Indicators, described by Hildebrandt et al. (2017), focus on the sequential use of biomass, evaluating the efficiency of material recycling and energy recovery across multiple stages of use. This approach highlights how effectively biomass is recycled and repurposed, promoting a cascading use model. However, since recycling and energy recovery are already considered in the standardized indicators, to avoid double counting, this indicator is not included in this deliverable. The Bioresource Utilization Index (Buind)

– developed by Vamza et al. (2021) – quantifies the efficiency of bioresource use by assessing the ratio of the mass of the main product and its by-products to the total mass of raw material input, taking into account the economic value of all products and by-products (following the bio-based value pyramid of Stegmann et al., 2020). Lastly, the Cascading Factor, introduced by Mantau, (2015), is calculated based on the overall resource balance of a region considering the available downstream processes, rather than tracing a specific amount of biomass input through subsequent cascading stages. Additionally, as this indicator is more applicable for macro-level analysis and thus, not relevant to this deliverable. In this deliverable, the first two interpretations of cascading combined are used, making the Biomass Utilization Factor and the Bioresource Utilization Index more applicable.

To address objective number six on the **risk minimization of hazardous substances accumulation**, it is important to note that although ISO 59020 does not include specific indicators for this aspect, it is comprehensively addressed through reporting guidelines on hazardous substances at different stages of a product's lifecycle. This approach will be followed in this deliverable, specifying data related to hazardous substances to be reported along with qualitative indicators.

At the material input stage, selecting materials and substances with low hazard profiles is crucial to facilitate safe and sustainable reuse, recycling, and repurposing. Product designers should prioritize materials that minimize potential risks to human health and the environment. Avoiding hazardous substances from the outset reduces potential complications in later stages. Organizations should utilize material declaration methods and tools, such as IEC 82474-1, to communicate information about hazardous substances through the value chain, ensuring all actors are well-informed and can handle materials appropriately.

During production, monitoring and reporting any hazardous substances used or created as by-products are essential. This includes ensuring that the chemical composition of all materials is well-documented and communicated to recycling, recovery, and recirculation organizations. Proper handling and treatment of hazardous substances are crucial to prevent contamination and to maintain safety when continuously cycling materials within the CE. Implementing common protocols for identifying and reporting hazardous substances helps maintain consistency and safety.

In the use phase, it is important to ensure that materials and substances within the product do not pose hazards over time. This involves assessing the risk of hazardous substance emissions to consumers and implementing measures to mitigate such risks during product use. Designing products with safe material choices also contributes to circularity by reducing the potential generation of hazardous waste at the end of their use phase.

At the end-of-life stage, detailed reporting on hazardous substances is necessary to determine appropriate recycling or disposal methods. Products should ideally be designed to be either mechanically or chemically recycled, or biodegradable and/or compostable, to ensure safe return to the biosphere. If a product contains hazardous substances that prevent recycling or safe disposal, it must be treated as hazardous waste, involving special handling and disposal procedures to avoid environmental contamination. Indicators such as the percentage of outflow that does not contain any substances of concern above relevant thresholds can help assess the circular characteristics of products at this stage. This approach will be followed in this deliverable, requiring data related to hazardous substances to be reported along with qualitative indicators.

3.1.3 Biological and Technical Cycling of Bio-based Products

This section investigates the product-level indicator typology for each important life cycle phase, differentiating between the critical properties of bioproducts that influence how indicators are utilised specifically in terms of biological/fossil-based feedstock, durable/consumable product, biological/technical cycling. The indicator categorisation in Table 4 enables a better understanding of which indicators should be measured at each lifecycle phase and in which scenarios they should be deployed, considering the different types of inputs, products, and EoL options (Table 4). Indicators measuring the circularity degree of the production process are not included in Table 4 as they are not related to the product-level typology.

Table 4: Appropriate Lifecycle Phases and Scenario for each Product-level Typology Circularity Indicator

Circularity Indicator	Input Materials		Use Phase		EoL	
	Bio-based	Fossil-based	Durable	Consumable	Technical cycling	Biological cycling
Reused content	✓	✓				
Pre-consumer recycled content	✓	✓				
Post-consumer recycled	✓	✓				

content						
Virgin renewable content	✓					
Circular input content	✓	✓				
Biomass Utilization Factor	✓				✓	✓
Bioresource Utilization Index	✓				✓	✓
Lifetime extension			✓			
Designed Reusability Rate			✓			
Actual Reuse			✓			
Designed Recyclability Rate					✓	
Actual Recycling					✓	
Actual Recirculation in Biological Cycle						✓
EoL Circularity					✓	✓
Hazardous substance reporting	✓	✓	✓	✓	✓	✓

The indicators in Table 4 (nano), combined with circular process indicators (micro), illustrate the actions that can be taken to achieve a fully circular product-level system. The results of these indicators measure the degree of circularity, informing supply chain actors about the actions they have taken to improve circularity and where they should focus more efforts to further enhance the circularity of their products and production systems.

3.2 Considerations For Supply Chain Actors

The product-level approach followed in this deliverable is designed to measure and assess the circularity of bio-based products produced by various actors within a supply chain, making it applicable to different BioReCer case studies and their associated actors. In this context, the term "product" does not refer exclusively to the final product of the supply chain but to the output of each actor. This output can either coincide with the final product of the supply chain or serve as the feedstock for the next actor in the chain. Consequently, a supply chain actor may need to calculate the circularity of either their products or their feedstock, especially if the circularity assessment was not completed by the previous actor. Figure 3 illustrates this approach, showing the transition between product and feedstock across different stages of the supply chain, from primary producers to intermediate and final producers, and including the post-consumer phase leading into either a new technical cycle or safe return to the biosphere. This approach underscores the continuous flow and transformation of materials, emphasizing both technical and biological cycles within a CE context.

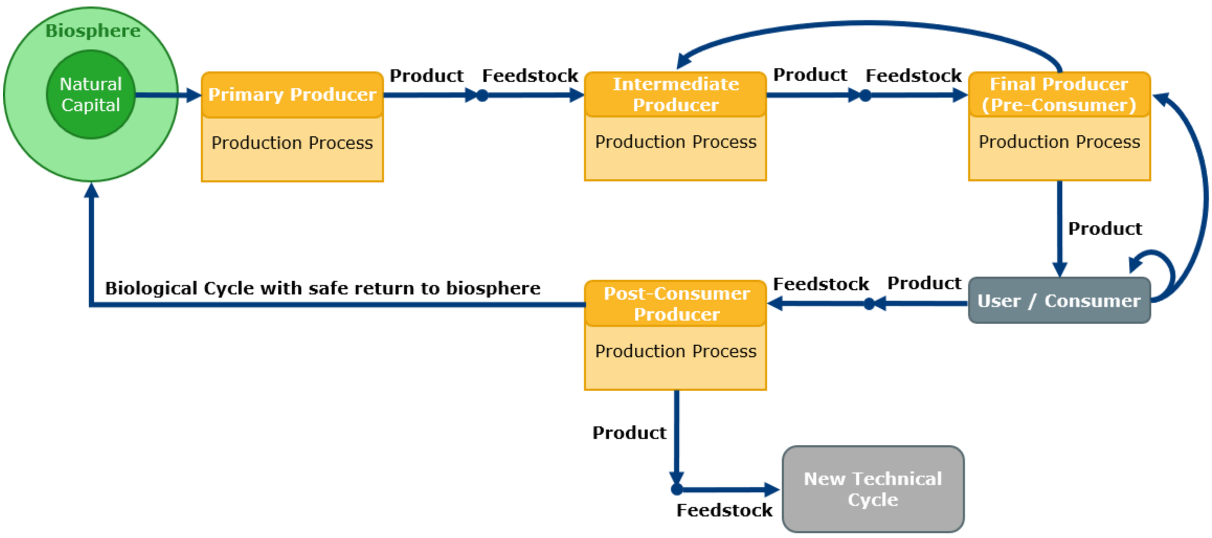

Figure 3: Transition of Products and Feedstock Across Supply Chain Stages.

To accurately calculate the circularity indicators of their products, different actors within the supply chain must consider specific factors. The actor's position in the supply chain significantly impacts the degree of information available to them, which in turn influences the importance of certain indicators over others. For example, primary producers may have detailed data on the sourcing and quality of raw materials but limited information on the end-of-life processes of their products. In contrast, final producers or post-consumer processors might have comprehensive insights into recycling and disposal practices but less visibility into the initial production stages. Additionally, product-level indicators can be applied to the feedstock, but the information required to calculate those indicators should be obtained from the previous actor(s) in the supply chain. This variability underscores the need for effective Track and Traceability systems and robust information transfer mechanisms from one actor to another. By ensuring seamless information flow across the supply chain, each actor can access the necessary data to accurately monitor, assess, enhance, or validate the circularity of their products. This approach not only supports comprehensive circularity assessments but also facilitates greater transparency and collaboration among supply chain partners.

3.2.1 Primary Producers

Primary producers in the bio-based sector generate products and by-products of biological origin to provide them to the next actor of the supply chain. In BioReCer, three main primary producers are involved, i.e. forestry producers, agricultural producers, and fish farmers (either wild fish catching or aquaculture).

Based on the developed circularity assessment methodology in section 3.1, circularity of a product depends on its source (measured by indicators related to the material inputs), its fate (measured by indicators related to its use and EoL), and the production process (measured by indicators related to circular production). Regarding their *source*, products of primary producers cannot be made from technically reused and recycled resources as they fundamentally originate from natural capital. These products are directly derived from essential elements provided by natural ecosystems, including soil, water, air, sunlight, and biodiversity.

Certified primary producers who follow sustainable practices can characterize their products as renewable and thus circular. When biomass produced with different sustainability credentials is mixed then *the sum of all consignments withdrawn from the mixture to be described as having the same sustainability characteristics, in the same quantities, as the sum of all consignments added to the mixture.* This approach from Directive (EU) 2018/2001 helps improve transparency and reduce administrative burdens in these cases. For example, if a primary production organization has certification for sustainable practices on 60% of their land, then 60% of their products should be characterized as renewable, assuming equal production among all productive land. However, if they can validate that they use regenerative practices and the resource's replenishment rate meets or exceeds its extraction rate, this proportion could be positively adjusted. Additionally, in cases where certified and non-certified biomass are sold separately (not mixed), if a primary producer can measure the exact productivity and prove that the certified land generates more or less than the non-certified land, then the products originating from the certified land can be characterized as 100% renewable and thus circular, while the rest would be considered 0% renewable unless they can validate the resource's replenishment rate meets or exceeds its extraction rate. This characterisation applies to all generated products (main and by-products).

As it is mentioned above, primary producers generate both main products and biomass by-products. In agriculture, forestry, and fishing these producers generate a variety of biomass by-products. In agriculture, common by-products include straw from grain crops, husks from nuts and grains, and manure from livestock. Traditionally, these by-products are often discarded, left to decompose, burned, or returned to the soil for nutrient replenishment. Forestry operations produce residues such as sawdust, bark, and wood chips from logging and milling activities, which are usually left on the forest floor or burned. In fishing, by-products consist of fish offal, heads, frames, and shells from shellfish, which are typically discarded at sea or processed minimally. It is evident that primary producers are the first supply chain actors who can contribute to biomass cascading, meaning they are critical to the utilization of the entire biomass for value-added applications. These biomass residues can be repurposed for uses such as animal feed, bioenergy, compost, and industrial applications, contributing to a CE by transforming them into valuable resources.

The circularity of biomass residues depends on several factors, including validation as renewable and sustainably produced (as previously explained), adherence to sustainable removal rates, and categorization as avoidable or unavoidable. Sustainable removal rates (White and Oldfield, 2016) ensure that the extraction of biomass residues does not negatively impact soil health, nutrient balance, or overall ecosystem functions thus, they vary significantly across different countries, type or residue, etc. For example, sustainable removal rates (estimated on a dry biomass basis) for wheat, barley, rye, and oats range between 30-60%, while for maize, it is approximately 40-60%, and for rapeseed and rice, it can be up to 60%. No specific data currently exist that estimate sustainable removal rates for fruit or vegetable crops. In forestry, sustainable removal rates for residues also vary by region and forest management practices. For example, in countries like the United Kingdom, Sweden, and Finland, up to 60-80% of forestry residues can be sustainably removed, whereas in other regions like Italy and Spain, the rates are generally lower, ranging from 20-40%.

Avoidable residues are material streams that could have been prevented with better management practices and are typically discarded due to inefficiencies within the primary production processes. In contrast, unavoidable residues are by-products that are inherently generated during the primary production process and cannot be prevented.

Examples of unavoidable residues include crop residues (e.g. straw, husk), vegetable residues (e.g. peels, leaves, stalks, vines), some manures, wood residues (e.g. sawdust, bark, wood chips, branches), and fishing by-products (e.g. fish offal, heads, frames, shrimp shells, crab shells).

Based on the above considerations, primary production residues that fall into the categories of validated renewable, sustainably removed, and unavoidable are characterised as 100% circular. Circularity degree decreases when these criteria are not fully met. For instance, if residues are only partially removed sustainably or are not fully validated as renewable, their circularity is reduced proportionately. Avoidable waste, although ideally should be minimized, is considered in this deliverable as 50% circular. This is because while avoidable waste should ideally be prevented, if it is not valorised, it will end up as waste, thereby losing the opportunity for resource recovery and contributing to inefficiency in the system. Therefore, even though avoidable waste should be minimized, its potential valorisation still contributes to the CE by transforming what would otherwise be waste into valuable resources.

Primary producers can also calculate the Biomass Utilisation Factor, as well as the Bioresource Utilisation Index (that adds to the Biomass Utilisation Factor by considering a value-added factor of each by-product according to the value-based pyramid) for the first stage of their outputs, either including or excluding the main product generated. The exclusion of the main products makes sense when the focus of product-based circularity is on the generated by-product(s). Another important indicator category for the primary producers is the circular production indicator category, including hazardous substances reporting which has the potential to significantly influence product value and circularity.

Primary producers can be excluded from the calculation of indicators related to the use phase and EoL of their valorised products, as these products often require additional processing by other producers before reaching the user/consumer. These subsequent producers may make significant modifications to the feedstock provided by primary producers, thereby altering the properties and impacts of the final product circularity. Consequently, primary producers may not have access to the necessary information to provide valid and comprehensive data for the entire lifecycle of their products. This separation ensures that each stage of the product lifecycle is evaluated by the most appropriate entity, maintaining accuracy and relevance in each lifecycle phase assessment.

3.2.2 Considerations For Pre-Consumer Producers

Pre-consumer producers obtain their primary feedstock from upstream actors, such as primary producers, which can be either virgin or residual materials. This positioning allows them to trace back their received feedstock to its primary production stage, enabling detailed characterisation of both feedstocks and products. This means assessments conducted by these actors are critical element for understanding the circularity performance of the value chain.

They can be categorized as either intermediate producers, who generate products requiring further treatment or processing to create the final product in the supply chain, or final producers, who generate the end product that is directly provided to the user or consumer. Most of the BioReCer case studies fall under this producer category. Examples of intermediate pre-consumer producers include pulp and paper industries and sawmills that use forestry materials and provide feedstock generated from their by-products to biorefineries, food industries that send their by-products to biofertiliser facilities, and composite wood producers who take agricultural residues to generate their products. Pre-consumer producers of BioReCer also include fish industries that use different fractions of fish catch to generate fish oil and collagen, and biorefineries that utilize forestry residues to generate bio-oil. Final pre-consumer producers of BioReCer include biofertiliser facilities that take agricultural residues and generate soil amendments for agricultural producers. Further considerations about this categorisation (i.e. intermediate and final producers) can be found in sub-section 3.2.4.

Specific Considerations for Pre-Consumer Producers:

1. **Biomass Utilisation Factor**: Pre-consumer producers can accurately calculate the biomass utilisation factor by considering the entire lifecycle of the primary biomass. This involves assessing how much of the biomass is converted into valuable products and by-products, including those that are recycled or reused.
2. **Characterisation of Circular Inflows**: Given their ability to trace feedstocks back to primary production, pre-consumer producers can effectively characterise circular inflows. This includes determining the percentage of inputs that are recycled, renewable, or derived from sustainable sources.
3. **Circularity Characterisation**: The circularity of inputs and outputs can be more accurately determined due to the availability of detailed information on the origin and processing of the biomass. This allows pre-consumer producers to better align with sustainable practices and characterise their products accordingly.

3.2.3 Considerations For Post-Consumer Producers

Post-consumer producers are involved in the processing and management of products after their initial use. They can be categorized as either intermediate or final producers, and the nature of the product – whether durable or consumable – affects the approach taken to circularity.

They are involved in the processing and management of products after their initial use. Intermediate post-consumer producers include recyclers, who process and convert post-consumer waste into reusable materials that require further treatment or processing by final producers of the same or a different supply chain. BioReCer examples of intermediate post-consumer producers include sewage sludge and other waste (e.g., OFMSW, agro-waste, non-hazardous organic liquid waste) biorefineries that generate volatile fatty acids (VFAs), polyhydroxyalkanoates (PHAs), and recovered phosphorus. Final post-consumer producers include remanufacturers, who restore used products to like-new condition and provide these refurbished products directly to the user or consumer. Additionally, final post-consumer producers can receive feedstock from intermediate post-consumer producers to generate products that can be re-introduced to the same or a different supply chain. By transforming waste materials and used products, post-consumer producers play a crucial role in extending the lifecycle of materials and reducing overall environmental impact. Further considerations about this categorisation can be found in sub-section 3.2.4.

Specific Considerations for Post-Consumer Producers:

Consumable Products:

1. **Previous Lifecycle Phase Biomass Utilisation**: For consumable products, the biomass utilisation factor is calculated starting from the point at which they receive the feedstock. The complexities and transformations undergone by these materials mean that tracing back to the primary production stage is often impractical or impossible.
2. **Circular Inflows Without Renewability Prerequisite**: Since the feedstock has already been utilized by consumers, its renewability is not a prerequisite for considering it circular. Post-consumer recycled materials contribute to circularity by preventing waste and enabling the reuse of resources, regardless of whether they are renewable.
3. **Complex Mixtures**: The feedstock for consumable post-consumer products often includes materials from various sources and processes. This heterogeneity complicates the characterisation of inputs, necessitating simplified and practical approaches to assess circularity.

Durable Products:

1. **Traceability of Feedstock**: For durable products, post-consumer producers may be able to trace back the feedstock to the primary biomass generation. This is

feasible due to the longer lifespan and potentially more detailed records associated with durable goods.

2. **Detailed Characterisation**: Similar to pre-consumer producers, post-consumer producers of durable products can provide detailed characterisation of circular inflows. This includes information on the renewability, recyclability, and origin of the feedstock.
3. **Circularity Characterisation**: Durable products, due to their traceability, can be assessed for circularity more accurately, aligning with methodologies used by pre-consumer producers.

3.2.4 Considerations For Intermediate and Final Producers

Intermediate and final producers play pivotal roles in the CE by further processing the feedstocks received from pre-consumer and post-consumer producers.

Intermediate producers cannot really predict the EoL of the final products but they can provide information about the designed attributes of their products. Intermediate producers, who create components or materials that will be used in final products, can provide information about the designed attributes of their products. These attributes include reusability, recyclability, and potential for refurbishment. While intermediate producers cannot predict the exact end-of-life (EoL) scenarios of final products, they can ensure that their materials are designed for optimal circularity.

Final producers, who create consumer-facing products, are responsible for calculating actual recirculation indicators. These indicators measure how much of the product, at the end of its life, is recycled, reused, or repurposed. Final producers must consider various factors, including consumer behavior and the effectiveness of recycling systems, to provide accurate assessments of EoL performance.

Specific Considerations for Intermediate and Final Producers:

1. **Designed Recirculation Indicators**: Intermediate producers can provide information about the designed attributes of their products, such as reusability, recyclability, and potential for refurbishment. They ensure that their materials are designed for optimal circularity, although they cannot predict the exact EoL scenarios of final products or the efficiency of cycling processes.
2. **Actual Recirculation Indicators**: Final producers are responsible for calculating actual recirculation indicators, measuring how much of the product, at the end of its life, is recycled, reused, or repurposed. They must consider various factors, including consumer behavior and the effectiveness of recycling systems, to provide accurate assessments of EoL performance.

3. **Holistic Circularity Evaluation**: Both intermediate and final producers must collaborate to ensure a holistic evaluation of circularity. Intermediate producers should focus on providing materials with high potential for recirculation, while final producers should implement effective EoL strategies to maximize the reuse and recycling of products.
4. **Nature of the Product (Durable vs. Consumable)**:
   - **Durable Products**: Intermediate producers of durable products should design for long life cycles, easy disassembly, and high recyclability. Final producers should implement robust take-back schemes and recycling programs.
   - **Consumable Products**: For consumables, the focus should be on using renewable or recycled inputs, minimizing waste during production, and ensuring that packaging and other materials are recyclable or biodegradable.

By incorporating these specific considerations into the development and selection of circularity indicators, primary producers, pre-consumer and post-consumer producers, along with intermediate and final producers, can more accurately and effectively contribute to the CE. This approach ensures that all stages of the product lifecycle are evaluated, promoting sustainability and resource efficiency throughout the bio-based sector.

3.3 Circularity Indicators Validation

The validation of circularity indicators is approached in a structured two-phase process to ensure robustness and applicability. In the first phase, the data requirements for each indicator are meticulously defined. This involves identifying the specific types of data needed to calculate each indicator accurately and demonstrating the availability and accessibility of this data. This phase establishes a foundation for the feasibility and relevance of the indicators by ensuring that the necessary data can be collected and utilized effectively.

The second phase of validation is planned for WP4 and WP6, where the bioproduct circularity indicators will be rigorously tested using BioReCer case studies. The comprehensive validation step in WP6 will involve applying the selected indicators to real-world scenarios within the bio-based sector, thereby showcasing their utility and practicality. The case studies will serve as a testing ground to evaluate how well the indicators perform in various contexts, uncovering any unforeseen issues or gaps. Furthermore, in WP4 a pilot audit is planned for BioReCer products and processes using the certification schemes developed in WP2. This will ensure the indicator frameworks developed are robust in certifying bio-based resources and help to identify any gaps that must be filled. This phase aims to refine the indicator set further by enabling the addition or removal of indicators based on empirical evidence and practical insights gathered during the case studies. Ultimately, this two-phase validation process is designed to ensure that the circularity indicators are both theoretically sound and practically applicable, enhancing their effectiveness in promoting CE practices within the bio-based sector.

4 Selected Circular Indicators for Bio-based Products

4.1 List of Selected Circular Indicators – Equations & Data Requirements

This section presents a comprehensive list of selected circular indicators essential for evaluating the circularity of bio-based products and processes. These indicators provide quantitative measures of various aspects of circularity, including resource efficiency, renewable resource utilization, waste minimization, and the effective management of end-of-life products. Each indicator is detailed with the equations used for calculation and the specific data requirements necessary for accurate and reliable assessment. This structured approach ensures that all relevant factors are considered, enabling a thorough and holistic evaluation of circular practices within the bio-based sector.

4.1.1 Material Input Indicators

Selected Material Input Indicators for Primary Producers

Selected indicators for Primary Producers of bio-based products and by-products only:

Verified virgin renewable product (%) – for main products:

$$\mathrm{VVREN(P)} = \frac{m_{\mathrm{VVEN(P)}}}{m_{\mathrm{P}}} \times 100 \qquad (1)$$

Where,

VVREN(P): the verified virgin renewable product of primary producers in %;

$m_{VVEN(P)}$: the dry mass of verified virgin renewable content of the primary producer's product, in kg or other mass unit;

m_P: the total dry mass of the product generated by the primary producer, in kg or other mass unit.

Circularity characterisation factor of residue (%) – for primary producer's by-products:

$$\mathrm{CCF(R)} = \frac{\mathrm{RENR} + \mathrm{SRR} + \mathrm{UNAVR} + 0.5 \times \mathrm{AVR}}{3} \qquad (2)$$

Where,

CCF(R): the circularity characterisation factor of the residue generated by primary producers and that is further utilised, in %;

RENR: the percentage of residue that is validated as renewable, in %;

SSR: the percentage of residue that is sustainably removed for further utilisation in line with the sustainable removal rate, in %;
UNAVR: the percentage of residue that is characterised as unavoidable residue, in %;
AVR: the percentage of residue that is characterised as avoidable residue, in %.

The Biomass Utilisation Factor was slightly modified for primary producers by changing the calculation from percentage-based to mass-based and by adding additional bioproducts that can be produced from biomass (i.e. bulk chemicals or pharmaceuticals). This modification presented in **equation (3)** is required to align with the value-based pyramid enabling simple derivation of **equation (5)**.

Modified Biomass Utilisation Factor of Primary Producers:

$$\mathrm{MBUF_0} = \frac{\mathbf{m_{BBP}} + \mathbf{m_{RtPFC}} + \mathbf{m_{RtFF}} + \mathbf{m_{RtBPP}} + \mathbf{m_{RtBCM}} + \mathbf{m_{RtEHF}} + \mathbf{m_{RtUF}}}{\mathbf{m_{TO}}} \quad (3)$$

Where,
$\mathbf{MBUF_0}$: the modified biomass utilisation factor for primary producers, unitless (defined as a ratio);
$\mathbf{m_{BBP}}$: the dry mass of the main bio-based product generated, in kg or other mass unit;
$\mathbf{m_{RtPFC}}$: the dry mass of the generated residue that is provided as feedstock for the generation of pharmaceuticals and fine chemicals, in kg or other mass unit;
$\mathbf{m_{RtFF}}$: the dry mass of the generated residue that is provided as feedstock for the generation of food and feed, in kg or other mass unit;
$\mathbf{m_{RtBPP}}$: the dry mass of the generated residue that is provided as feedstock for the generation of bioplastics and polymers, in kg or other mass unit;
$\mathbf{m_{RtBCM}}$: the dry mass of the generated residue that is provided as feedstock for the generation of bulk chemicals and materials, in kg or other mass unit;
$\mathbf{m_{RtEHF}}$: the dry mass of the generated residue that is provided as feedstock for the generation of energy, heat and fuels, in kg or other mass unit;
$\mathbf{m_{RtUF}}$: the dry mass of the generated residue that is usefully utilised in biosphere according to the sustainably remaining residue rate, in kg or other mass unit;
$\mathbf{m_{TO}}$: the total dry mass of outputs (all products and by-products) generated by the primary producer, in kg or other mass unit.

The total mass of outputs generated by the primary producer can be calculated as follows:

$$\mathbf{m_{TO}} = \mathbf{m_{BBP}} + \mathbf{m_{RtPFC}} + \mathbf{m_{RtFF}} + \mathbf{m_{RtBPP}} + \mathbf{m_{RtBCM}} + \mathbf{m_{RtEHF}} + \mathbf{m_{RtUF}} + \mathbf{m_W} \quad (4)$$

Where,

m_W: the dry mass of remaining outputs (e.g. products, by-products, etc.) that are not usefully utilised neither in the biosphere nor in the technosphere (often referred as waste), in kg or other mass unit. *An example is the mass of residues that is burnt onsite, or residue left onsite that exceeds the sustainably remaining residue rate*.

Based on **equation (3)**, the value-based biomass utilisation factor – adapted by the Bioresource Utilisation Index – can be calculated using the **equation (5)** below.

Value-based Biomass Utilisation Factor following the bio-based value pyramid:

$$\mathbf{VMBUF_0} = \frac{\mathbf{m_{BBP} + m_{RtPFC} \times 1 + m_{RtFF} \times 0.8 + m_{RtBPP} \times 0.6 + m_{RtBCM} \times 0.4 + m_{RtEHF} \times 0.2 + m_{RtUF} \times 1}}{\mathbf{m_{TO}}} \quad \textbf{(5)}$$

The primary producer should provide the contribution of each individual product and by-product to the total generated output to the relevant downstream supply chain actor(s), calculated as follows:

$$\mathbf{BO(X)_{n+1}} = \frac{\mathbf{m_X}}{\mathbf{m_{TO}}} \times \mathbf{100} \quad \textbf{(6)}$$

$$\mathbf{VBO(X)_{n+1}} = \frac{\mathbf{m_X}}{\mathbf{m_{TO}}} \times c_X \times \mathbf{100} \quad \textbf{(7)}$$

Where,

$BO(X)_{n+1}$: the product/by-product X that will be utilised as input by the next actor as a percentage of the total produced output, in %;

m_X: the dry mass of the relevant product or by-product X in which the downstream actor is interested (e.g. m_{BBP}, m_{RtPFC}, m_{RtFF}, m_{RtBPP}, m_{RtBCM}, m_{RtEHF}, m_{RtUF}), in kg or other mass unit;

$VBO(X)_{n+1}$: the value-added of the product/by-product X that will be utilised as input by the next actor as a percentage of the total produced output, in %;

c_X: the coefficient assigned to the utilisation of product or by-product X based on the bio-based value pyramid.

Selected Material Input Indicators for Pre- and Post-Consumer Intermediate and Final Producers

Each supply chain actor receiving feedstock for the generation of their products should perform a characterisation of their inputs (i.e. feedstocks) and outputs (i.e. products and by-products) to calculate the circularity indicators presented in **equations (8)-(28)**.

Selected indicators of **bio-based products** – related to all types of pre- and post-consumer producers:

Reused content of product (%):

$$\mathbf{REUC(P) = \frac{m_{REUC(P)}}{m_P} \times CC(P)_{n-1}} \quad \textbf{(8)}$$

Where,

REUC(P): the reused content of product, in %;

$m_{REUC(P)}$: the dry mass of product that originates from reused inputs, in kg or other mass unit;

m_P: the total dry mass of product, in kg or other mass unit;

$CC(P)_{n-1}$: the circular content – equation (15) – of the specific reused input obtained by the previous actor that provides this input, in %.

Pre-consumer recycled bio-based content of product (%):

$$\mathbf{PRRECBBC(P) = \frac{m_{PRERECBBC(P)}}{m_P} \times CCF(BBB)_{n-1}} \quad \textbf{(9)}$$

Where,

PRRECBBC(P): the pre-consumer recycled bio-based content of product, in %;

$m_{PRERECBBC(P)}$: the dry mass of product that originates from pre-consumer recycled bio-based inputs, in kg or other mass unit;

$CCF(BBB)_{n-1}$: the circularity characterisation factor of pre-consumer bio-based by-product obtained by the previous actor (i.e. the supplier of pre-consumer recycled bio-based input), in %.

Post-consumer recycled fossil-based content of product (%):

$$\mathrm{PORECFBC(P)} = \frac{\mathrm{m_{POERECFBC(P)}}}{\mathrm{m_P}} \times \mathrm{CCF(FBB)_{n-1}} \quad \textbf{(10)}$$

Where,

PORECFBC(P): the post-consumer recycled fossil-based content of product, in %;

$\mathbf{m_{PRERECFBC(P)}}$: the dry mass of product that originates from post-consumer recycled fossil-based inputs, in kg or other mass unit;

$\mathbf{CCF(FBB)_{n-1}}$: the circularity characterisation factor of post-consumer fossil-based by-product obtained by the previous actor (i.e. the supplier of post-consumer recycled fossil-based input), in %.

Post-consumer recycled bio-based content of product (%):

$$\mathrm{PORECC(P)} = \frac{\mathrm{m_{POSTRECC(P)}}}{\mathrm{m_P}} \times \mathrm{CCF(POB)_{n-1}} \quad \textbf{(11)}$$

Where,

PORECC(P): the post-consumer recycled content of product, in %;

$\mathbf{m_{POSTRECC(P)}}$: the dry mass of product that originates from post-consumer recycled inputs, in kg or other mass unit;

$\mathbf{CCF(POB)_{n-1}}$: the circularity characterisation factor of post-consumer by-product obtained by the previous actor (i.e. the supplier of post-consumer recycled input), in %.

Virgin renewable content of product (%):

$$\mathrm{VRENC(P)} = \frac{\mathrm{m_{VRENC(P)}}}{\mathrm{m_P}} \times \mathrm{VVREN(P)} \quad \textbf{(12)}$$

Where,

VRENC(P): the virgin renewable content of the product, in %;

$\mathbf{m_{VRENC(P)}}$: the dry mass of product that originates from virgin renewable inputs, in kg or other mass unit.

Content of Primary Producers' Circular Residue in Product (%):

$$\mathbf{PPRESC(P)} = \frac{\mathbf{m_{PPRESC(P)}}}{\mathbf{m_P}} \times \mathbf{CCF(R)} \qquad \mathbf{(13)}$$

Where,

PPRESC(P): the content of primary producer's circular residue in product, in %;

$\mathbf{m_{PPRESC(P)}}$: the dry mass of product that originates from circular residual inputs obtained by primary producers, in kg or other mass unit.

The total dry mass of product generated can be calculated as follows:

$$\mathbf{m_P} = \mathbf{m_{REUC(P)}} + \mathbf{m_{PRERECBBC(P)}} + \mathbf{m_{PRERECFBC(P)}} + \mathbf{m_{POSTRECC(P)}} + \mathbf{m_{VRENC(P)}} + \mathbf{m_{PPRESC(P)}} + \mathbf{m_V} \qquad \mathbf{(14)}$$

Where,

$\mathbf{m_V}$: the dry mass of product that originates from virgin non-renewable inputs (whether they are fossil-based or unverified renewable), in kg or other mass unit.

Circular Content of Product (%):

$$\mathbf{CC(P)} = \mathbf{REUC(P)} + \mathbf{PRRECBBC(P)} + \mathbf{PORECFBC(P)} + \mathbf{PORECC(P)} + \mathbf{VRENC(P)} + \mathbf{PPRESC(P)} \qquad \mathbf{(15)}$$

Where,

CC(P): the circular content of the product, in %.

Selected indicators of **by-products** sent for further utilisation in a different supply chain actor:

Circularity characterisation factor of pre-consumer bio-based by-product (%):

$$\mathbf{CCF(BBB)_n} = \frac{\mathbf{RCSR_{BBB}} + \mathbf{UNAVR_{BBB}} + \mathbf{0.5} \times \mathbf{AVR_{BBB}}}{\mathbf{2}} \qquad \mathbf{(16)}$$

Where,

$\mathbf{CCF(BBB)_n}$: the circularity characterisation factor of pre-consumer bio-based by-product generated by the current supply chain actor, in %.

$\mathbf{RCSR_{BBB}}$: the portion of the total dry mass of bio-based by-product that originates from validated renewable inputs and circular secondary resources, in %. $RCSR_{BBB}$ is the equivalent of equation (15) for the by-product – meaning that for each by-product, equations (8)-(15) need to be calculated;;

$UNAVR_{BBB}$: the portion of the total dry mass of bio-based by-product that is characterised as unavoidable by-product, in %;
AVR_{BBB}: the portion of the total dry mass of bio-based by-product that is characterised as avoidable by-product, in %.

Circularity characterisation factor of post-consumer fossil-based by-product (%):

$$CCF(FBB)_n = UNAVR_{FBB} + 0.5 \times AVR_{FBB} \quad (17)$$

Where,
$CCF(FBB)_n$: the circularity characterisation factor of post-consumer fossil-based by-product generated by the current supply chain actor, in %.
$UNAVR_{FBB}$: the portion of the total dry mass of fossil-based by-product that is characterised as unavoidable by-product, in %;
AVR_{FBB}: the portion of the total dry mass of fossil-based by-product that is characterised as avoidable by-product, in %.

Circularity characterisation factor of post-consumer bio-based by-product (%):

$$CCF(POB)_n = \frac{ROFR_{POB} + SRUR_{POB} + UNAVR_{POB} + 0.5 \times AVR_{POB}}{3} \quad (18)$$

Where,
$CCF(POB)_n$: the circularity characterisation factor of post-consumer by-product generated by the current supply chain actor, in %.
$ROFR_{POB}$: percentage of the organic fraction of post-consumer by-product validated as renewable, in %.
$SRUR_{POB}$: percentage of post-consumer by-product that is sustainably recovered for further utilisation, in %.
$UNAVR_{POB}$: the portion of the total dry mass of post-consumer by-product that is characterised as unavoidable by-product, in %;
AVR_{POB}: the portion of the total dry mass of post-consumer by-product that is characterised as avoidable by-product, in %.

Intermediate and Final Producers dealing with a specific type of bio-based feedstock (biomass) can calculate the Biomass Utilisation Contribution of the current actor, using **equation (19)** below.

Biomass Utilisation Contribution of Intermediate (and Final) Producers:

$$\mathbf{BUC_n = EF_{n(t)}\ x\ BO(X)_{n-1}} \qquad \textbf{(19)}$$

Where,

BUC$_n$: the biomass contribution factor of intermediate and final producers by the current actor, unitless (defined as a ratio);

BO(X)$_{n-1}$: the product/by-product X that is further utilised by another actor as a percentage of the total primary producer's generated output as calculated by the previous actor, in %;

EF$_{n(t)}$: the total production efficiency of the current actor in producing valuable products and by-products, unitless (estimated as a ratio) and calculated using **equation (20)** below.

Total production efficiency of the current actor in producing valuable products and by-products:

$$\mathbf{EF_{n(t)}} = \frac{\begin{array}{c}(\mathbf{m_{BBP1}} + \cdots + \mathbf{m_{BBPz}}) + (\mathbf{m_{BBtPFC1}} + \cdots + \mathbf{m_{BBtPFCz}}) + (\mathbf{m_{BBtFF1}} + \cdots + \mathbf{m_{BBtFFz}}) \\ + (\mathbf{m_{BBtBPP1}} + \cdots + \mathbf{m_{BBtBPPz}}) + (\mathbf{m_{BBtBCM1}} + \cdots + \mathbf{m_{BBtBCMz}}) \\ + (\mathbf{m_{BBtEHF1}} + \cdots + \mathbf{m_{BBtEHFz}}) + (\mathbf{m_{BBtUF1}} + \cdots + \mathbf{m_{BBtUFz}})\end{array}}{\mathbf{m_{TBI}}} \qquad \textbf{(20)}$$

Where,

m$_{BBP1z}$: the dry mass of the main bio-based product(s) generated originating from the utilised biomass, in kg or other mass unit;

m$_{BBtPFCz}$: the dry mass of the generated by-product(s) originating from the utilised biomass that is provided as feedstock for the generation of pharmaceuticals and fine chemicals, in kg or other mass unit;

m$_{BBtFFz}$: the dry mass of the generated by-product(s) originating from the utilised biomass that is provided as feedstock for the generation of food and feed, in kg or other mass unit;

m$_{BBtBPPz}$: the dry mass of the generated by-product(s) originating from the utilised biomass that is provided as feedstock for the generation of bioplastics and polymers, in kg or other mass unit;

m$_{RtBCM}$: the dry mass of the generated by-product(s) originating from the utilised biomass that is provided as feedstock for the generation of bulk chemicals and materials, in kg or other mass unit;

m$_{BBtEHFz}$: the dry mass of the generated by-product(s) originating from the utilised biomass that is provided as feedstock for the generation of energy, heat and fuels, in kg or other mass unit;

m_{BBtUFz}: the dry mass of the generated by-product(s) originating from the utilised biomass that is usefully utilised in biosphere according to the sustainably remaining residue rate, in kg or other mass unit;

m_{TBI}: the total dry mass of biomass input to the current actor used to generate all the above products and by-products, in kg or other mass unit.

Value-based Biomass Utilisation Contribution (VMBUC)n:

$$\mathbf{VBUC_n = VBO(X)_{n-1}\ x\ VEF_{n(t)}} \tag{21}$$

Where,

$VBUC_n$: the contribution of the current actor to the value-added of the actual biomass utilisation, in %.

$VBO(X)_{n-1}$: the value-added of the utilised product/by-product X as a percentage of the total primary producer's generated output as calculated by the previous actor, in %;

$VEF_{n(t)}$: the total production efficiency of the current actor in producing valuable products and by-products sent to added value applications, unitless (estimated as a ratio) and calculated using **equation (22)** below.

Total production efficiency of the current actor in producing valuable products and by-products sent to added value applications:

$$\mathbf{VEF_{n(t)}} = \frac{\begin{array}{c}\sum_{i=1}^{z} \mathbf{m_{BBPi}} + \sum_{i=1}^{z}(\mathbf{m_{BBtPFCi}} \times 1) + \sum_{i=1}^{z}(\mathbf{m_{BBtFFi}} \times 0.8) \\ + \sum_{i=1}^{z}(\mathbf{m_{BBtBPPi}} \times 0.6) + \sum_{i=1}^{z}(\mathbf{m_{BBtBCMi}} \times 0.4) + \sum_{i=1}^{z}(\mathbf{m_{BBtEHFi}} \times 0.2) + \sum_{i=1}^{z}(\mathbf{m_{BBtUFi}})\end{array}}{\mathbf{m_{TBI}}} \tag{22}$$

The pre-consumer producer should provide the contribution of each individual product and by-product in relation to the total primary producer's generated output (m_{TO}) to the relevant downstream supply chain actor(s), calculated as follows:

$$\mathbf{BO(X)_{n+1}} = \frac{\mathbf{m_X}}{\mathbf{m_{TO}}} \times \mathbf{100} \tag{23}$$

$$\mathbf{VBO(X)_{n+1}} = \frac{\mathbf{m_X}}{\mathbf{m_{TO}}} \times c_X \times \mathbf{100} \tag{24}$$

Where,

$BO(X)_{n+1}$: the product/by-product X that will be utilised as input by the next actor as a percentage of the total primary producer's generated output, in %;

m_X: the dry mass of the relevant product or by-product X in which the downstream actor is interested (e.g. m_{BBP}, m_{RtPFC}, m_{RtFF}, m_{RtBPP}, m_{RtBCM}, m_{RtEHF}, m_{RtUF}), in kg or other mass unit;
$VBO(X)_{n+1}$: the value-added of the product/by-product X that will be utilised as input by the next actor as a percentage of the total primary producer's generated output, in %;
c_X: the coefficient assigned to the utilisation of product or by-product X based on the value based pyramid.

There are certain supply chain actors that receive feedstocks, such as **sewage sludge, OFMSW, and organic liquid waste**, which are complex mixtures of various biomass sources that have undergone significant transformations. These types of feedstocks are challenging to trace back to their primary production. In this deliverable, for biorefineries receiving these types of feedstocks, the cascading stage of feedstock utilization is considered to start at the point of their input, rather than tracing back to the virgin biomass production. In these cases, instead of using **equations (19)-(24)**, **equations (25)-(28)** are used as presented below.

Modified Biomass Utilisation Factor for supply chain actors dealing with complex biomass mixtures:

$$\mathbf{MBUF_0 = \frac{m_{PFC} + m_{FF} + m_{BPP} + m_{BCM} + m_{EHF} + m_{UF}}{m_{TBI}}} \quad \textbf{(25)}$$

Where,
$MBUF_0$: the modified biomass utilisation factor, unitless (defined as a ratio);
m_{PFC}: the (dry) mass of the generated (by-)product sent to pharmaceuticals and fine chemicals production, in kg or other mass unit;
m_{FF}: the (dry) mass of the generated (by-)product sent to food and feed production, in kg or other mass unit;
m_{BPP}: the (dry) mass of the generated (by-)product sent to bioplastics and polymers production, in kg or other mass unit;
m_{BCM}: the (dry) mass of the generated (by-)product sent to bulk chemicals and materials, in kg or other mass unit;
m_{EHF}: the (dry) mass of the generated (by-)product sent to energy, heat and fuels, in kg or other mass unit;
m_{UF}: the (dry) mass of the generated (by-)product that is usefully utilised in biosphere, in kg or other mass unit;

m_{TBI}: the total dry mass of biomass input to the current actor used to generate all the above products and by-products, in kg or other mass unit.

In the Value-based Biomass Utilisation Factor, the coefficients assigned to the different uses of the (by-)products are not the same as in equations (5) and (25), as biorefineries dealing with such complex feedstocks are often restricted from generating products for high-value applications (e.g., food and feed, cosmetics, etc.). Therefore, in these cases, bioplastics and polymers are considered among the highest value applications, with the least favourable being energy, heat, and fuels.

The Value-based Biomass Utilisation Factor for biorefineries dealing with complex mixtures as feedstocks:

$$\mathbf{VMBUF_0} = \frac{\mathbf{m_{PFC} \times 1 + m_{FF} \times 1 + m_{BPP} \times 1 + m_{BCM} \times 0.8 + m_{EHF} \times 0.4 + m_{UF} \times 0.6}}{\mathbf{m_{TBI}}} \quad \textbf{(26)}$$

The current actor should provide the contribution of each individual product and by-product to the total received inputs to the relevant downstream supply chain actor(s), calculated as follows:

$$\mathbf{BO - B(X)_{n+1}} = \frac{\mathbf{m_X}}{\mathbf{m_{TBI}}} \times \mathbf{100} \quad \textbf{(27)}$$

$$\mathbf{VBO - B(X)_{n+1}} = \frac{\mathbf{m_X}}{\mathbf{m_{TBI}}} \times c_X \times \mathbf{100} \quad \textbf{(28)}$$

Where,

BO-B(X)$_{n+1}$: the product/by-product X that will be utilised as input by the next actor as a percentage of the total received input, in %;

m_X: the (dry) mass of the relevant product or by-product X in which the downstream actor is interested (e.g. m_{BBP}, m_{RtPFC}, m_{RtFF}, m_{RtBPP}, m_{RtBCM}, m_{RtEHF}, m_{RtUF}), in kg or other mass unit;

VBO-B(X)$_{n+1}$: the value-added of the product/by-product X that will be utilised by the next actor as a percentage of the total received input, in %;

c_X: the coefficient assigned to the utilisation of product or by-product X based on the bio-based value pyramid.

4.1.2 Circular Production Indicators

Each supply chain actor should consider their additional inputs to their processes to calculate the circular production indicators presented in **equations (29)-(39)**.

Energy-related Indicators

The energy-related indicators are presented in **equations (29)-(31)**.

Average renewable energy consumed in the total production process for the generated product:

$$\mathbf{REC} = \frac{\mathbf{RE_I} - \mathbf{RE_O}}{\mathbf{TE_I} - \mathbf{TE_O}} \times \mathbf{100} \qquad \textbf{(29)}$$

Where,

REC: the average energy consumed by the total production process that is renewable energy, in %;

RE_I: the renewable energy inflow, in MJ or kWh;

RE_O: the renewable energy outflow, in MJ or kWh;

TE_I: the total energy inflow, in MJ or kWh;

TE_O: the total energy outflow, in MJ or kWh.

Energy Intensity to produce the product:

$$\mathbf{EI} = \frac{\mathbf{TE_I}}{\mathbf{n_P}} \qquad \textbf{(30)}$$

Where,

EI: the energy intensity during the reference time period, in MJ or kWh;

TE_I: the total energy inflow during the reference time period, in MJ or kWh;

n_P: is the number of unit products, n, produced during the reference time period.

Energy Intensity performance in comparison to industry average:

$$\mathbf{EIP} = \frac{\mathbf{EI}}{\mathbf{EI_{IA}}} \qquad \textbf{(31)}$$

Where,

EIP: the energy intensity performance;

EI_{IA}: the industry average energy intensity.

Water-related Indicators

Circular water withdrawal for the total production process for the generated product:

$$\mathrm{CWW} = \frac{\mathrm{CWI}}{\mathrm{TWI}} \times 100 \tag{32}$$

Where,

CWW: the average water withdrawal from circular sources, in %;

CWI: the volume of water inflow from circular sources, in m^3/year;

TWI: the volume of water inflow (external) from all sources (circular and linear), in m^3/year.

Circular water sources include: water from a non-virgin source, including reused or recycled water from a third party, water from a renewable freshwater source, such as surface, ground and harvested rainwater that is renewed by precipitation and the natural water cycle, non-freshwater natural sources such as sea or brackish water, and water in raw materials or extracted from a product.

Circular water discharge for the total production process for the generated product:

$$\mathrm{CWD} = \frac{\mathrm{CWO}}{\mathrm{TWI}} \times 100 \tag{33}$$

Where,

CWD: the average circular water discharges, in %.

CWI: the volume of water discharges considered as circular, in m^3/year.

Circular water discharges include: water that is reused or recycled by another organization or returned to the water source at the same or better quality level as extracted, according to local regulatory limits. Non-circular outflows include: losses and releases such as effluents, spillage, or evaporation that are not returned to the local water source, and water incorporated into products that does not return to the origin at high quality.

Internal water recirculation or reuse in the total production process of the product:

$$\mathrm{IWR} = \frac{\mathrm{TWU}}{\mathrm{TWI}} \qquad (34)$$

Where,

IWR: the ratio of water reused or recycled within the production process of the generated product after being stored and treated as required, dimensionless;

TWU: the total volume of water used and consumed in all processes and operations for the generation of the product, in m^3/year.

Water Intensity to produce the product:

$$\mathrm{WI} = \frac{\mathrm{TW_I}}{\mathrm{n_P}} \qquad (35)$$

Where,

WI: the water intensity during the reference time period, in m^3 or L;

TW_I: the total water inflow during the reference time period, in m^3 or L;

n_P: is the number of unit products, n, produced during the reference time period.

Water Intensity performance in comparison to industry average:

$$\mathrm{WIP} = \frac{\mathrm{WI}}{\mathrm{WI_{IA}}} \qquad (36)$$

Where,

WIP: the water intensity performance;

WI_{IA}: the industry average water intensity.

Process-Function Chemicals (and other materials) Indicators

Circular process-function chemical(s)/material(s) input for the total production process of the generated product:

$$\mathrm{CPFC/M} = \frac{\mathrm{REU_{PFC/M}} + REC_{PFC/M} + BBR_{PFC/M}}{\mathrm{TPFC/M}} \times 100 \qquad (37)$$

Where,

CPFC/M: the average circular process-function chemical(s)/material(s) input in the total production process of the product, in %;

$REU_{PFC/M}$: the mass of reused chemical(s)/materials(s) utilised in the total production process of the product, in kg or other mass unit;

$REC_{PFC/M}$: the mass of recycled chemical(s)/materials(s) utilised in the total production process of the product, in kg or other mass unit;

$BBR_{PFC/M}$: the mass of renewable bio-based chemical(s)/materials(s) utilised in the total production process of the product, in kg or other mass unit;

TPFC/M: the mass of all input chemical(s)/material(s) used in the total production process of the product, in kg or other mass unit.

Process-function chemical(s)/material(s) Intensity to produce the product:

$$\mathrm{PFC/MI} = \frac{\mathrm{TPFC/M_I}}{\mathrm{n_P}} \quad (38)$$

Where,

PFC/MI: the process-function chemical(s)/material(s) intensity during the reference time period, in kg or other mass unit;

$TPFC/M_I$: the total process-function chemical(s)/material(s) input during the reference time period, in kg or other mass unit;

n_P: is the number of unit products, n, produced during the reference time period.

Process-function chemical(s)/material(s) Intensity performance in comparison to industry average:

$$\mathrm{PFC/MIP} = \frac{\mathrm{PFC/MI}}{\mathrm{PFC/MI_{IA}}} \quad (39)$$

Where,

PFC/MIP: the process-function chemical(s)/material(s) intensity performance;

PFC/MI_{IA}: the industry average process-function chemical(s)/material(s) intensity.

4.1.3 Use Phase Indicators

Use phase indicators target mainly **durable products** as these products are designed to last for an extended period of time. Use phase indicators can be estimated more accurately by producers generating final products. However, intermediate producers may also provide some indicative calculations (focusing on the average lifetime, designed reusability and designed remanufacturing and refurbishment indicators) regarding their durable products as the durability, remanufacturing, and reusability of a final product often depend on the characteristics of its materials (i.e. products of intermediate producers). Final producers are expected to calculate all indicators using **equations (40)-(44)**.

Average Lifetime of product in comparison to industry average:

$$ALTR_P = \frac{LT_P}{LT_{IA}} \quad (40)$$

Where,

$ALTR_P$: the lifetime ratio of the product in comparison to industry average, dimensionless;

LT_P: the lifetime of the product, in years;

LT_{IA}: the industry average lifetime of the product, in years.

Designed reusability of a product:

$$DREU_P = \frac{m_{DREUP}}{m_{TP}} \times 100 \quad (41)$$

Where,

$DREU_P$: the percent of the product mass designed for reuse, in %;

m_{DREUP}: the dry mass of product that is designed for reuse, in kg or other mass unit;

m_{TP}: the total dry mass of the product, in kg or other mass unit.

Actual reusability of a product:

$$AREU_P = \frac{m_{REUP}}{m_{TP}} \times 100 \quad (42)$$

Where,

$AREU_P$: the percent of actual reused parts of product, in %;

$\mathbf{m_{REUP}}$: the dry mass of product that is reused, in kg or other mass unit.

Designed refurbishing and remanufacturing of a product:

$$DRR_P = \frac{m_{DRRP}}{m_{TP}} \times 100 \quad (43)$$

Where,

$\mathbf{DRR_P}$: the percent of the product mass designed for refurbishing and remanufacturing, in %;

$\mathbf{m_{DRRP}}$: the dry mass of product that is designed for refurbishing and remanufacturing, in kg or other mass unit.

Actual refurbishing and remanufacturing of a product:

$$ARR_P = \frac{m_{ARRP}}{m_{TP}} \times 100 \quad (44)$$

Where,

$\mathbf{ARR_P}$: the percent of the product mass that is actually refurbished and/or remanufactured, in %;

$\mathbf{m_{ARRP}}$: the dry mass of product that is actually refurbished and/or remanufactured, in kg or other mass unit.

4.1.4 End-of-Life Indicators

Product's EoL indicators are expected to be calculated by both intermediate and final producers. Following a similar approach to use phase indicators, intermediate producers are expected to calculate the designed recirculation indicators, while final producers should calculate both designed and actual recirculation indicators presented in **equations (45)-(56)**.

Designed Recirculation of product at the EoL as pharmaceutical and fine chemical:

$$DRaPFC = \frac{dm_{PtPFC}}{m_{TP}} \times 100 \quad (45)$$

Where,

DRaPFC: the designed recirculation of product at the EoL as pharmaceutical and fine chemical, %;

dm_{PtPFC}: the designed (dry) mass of the product that can be further utilised after the EoL to produce pharmaceuticals and fine chemicals, in kg or other mass unit;

m_{TP}: the total dry mass of the product, in kg or other mass unit.

Actual Recirculation of product at the EoL as pharmaceutical and fine chemical:

$$\mathrm{ARaPFC} = \frac{\mathrm{am_{PtPFC}}}{\mathrm{m_{TP}}} \times 100 \qquad \textbf{(46)}$$

Where,

ARaPFC: the actual recirculation of product at the EoL as pharmaceutical and fine chemical, %;

am_{PtPFC}: the actual (dry) mass of the product that is further utilised after the EoL to produce pharmaceuticals and fine chemicals, in kg or other mass unit.

Designed Recirculation of product at the EoL as food and feed:

$$\mathrm{DRaFF} = \frac{\mathrm{dm_{PtFF}}}{\mathrm{m_{TP}}} \times 100 \qquad \textbf{(47)}$$

Where,

DRaFF: the designed recirculation of product at the EoL as food and feed, %;

dm_{PtFF}: the designed (dry) mass of the product that can be further utilised after the EoL to produce food and feed, in kg or other mass unit;

m_{TP}: the total dry mass of the product, in kg or other mass unit.

Actual Recirculation of product at the EoL as food and feed:

$$\mathrm{ARaFF} = \frac{\mathrm{am_{PtFF}}}{\mathrm{m_{TP}}} \times 100 \qquad \textbf{(48)}$$

Where,

ARaPFC: the actual recirculation of product at the EoL as food and feed, %;

am_{PtPFC}: the actual (dry) mass of the product that is further utilised after the EoL to produce food and feed, in kg or other mass unit.

Designed Recirculation of product at the EoL as bioplastics and polymers:

$$\mathbf{DRaBBP} = \frac{\mathbf{dm_{PtBPP}}}{\mathbf{m_{TP}}} \times \mathbf{100} \quad \textbf{(49)}$$

Where,

DRaBBP: the designed recirculation of product at the EoL as bioplastics and polymers, %;

$\mathbf{dm_{PtBBP}}$: the designed (dry) mass of the product that can be further utilised after the EoL to produce bioplastics and polymers, in kg or other mass unit;

$\mathbf{m_{TP}}$: the total dry mass of the product, in kg or other mass unit.

Actual Recirculation of product at the EoL as bioplastics and polymers:

$$\mathbf{ARaBPP} = \frac{\mathbf{am_{PtBPP}}}{\mathbf{m_{TP}}} \times \mathbf{100} \quad \textbf{(50)}$$

Where,

ARaBPP: the actual recirculation of product at the EoL as bioplastics and polymers, %;

$\mathbf{am_{PtBPP}}$: the actual (dry) mass of the product that is further utilised after the EoL to produce bioplastics and polymers, in kg or other mass unit.

Designed Recirculation of product at the EoL as bulk chemicals and materials:

$$\mathbf{DRaBCM} = \frac{\mathbf{dm_{PtBCM}}}{\mathbf{m_{TP}}} \times \mathbf{100} \quad \textbf{(51)}$$

Where,

DRaBCM: the designed recirculation of product at the EoL as bulk chemicals and materials, %;

$\mathbf{dm_{PtBCM}}$: the designed (dry) mass of the product that can be further utilised after the EoL to produce bulk chemicals and materials, in kg or other mass unit;

$\mathbf{m_{TP}}$: the total dry mass of the product, in kg or other mass unit.

Actual Recirculation of product at the EoL as bulk chemicals and materials:

$$\mathbf{ARaBCM} = \frac{\mathbf{am_{PtBCM}}}{\mathbf{m_{TP}}} \times \mathbf{100} \quad \textbf{(52)}$$

Where,

ARaBCM: the actual recirculation of product at the EoL as bulk chemicals and materials, %;

$\mathbf{am_{PtBCM}}$: the actual (dry) mass of the product that is further utilised after the EoL to produce bulk chemicals and materials, in kg or other mass unit.

Designed Recirculation of product at the EoL as energy, heat and fuels:

$$\mathbf{DRaEHF = \frac{dm_{PtEHF}}{m_{TP}} \times 100} \quad \mathbf{(53)}$$

Where,

DRaEHF: the designed recirculation of product at the EoL as energy, heat and fuels, %;

$\mathbf{dm_{PtEHF}}$: the designed (dry) mass of the product that can be further utilised after the EoL to produce energy, heat and fuels, in kg or other mass unit;

$\mathbf{m_{TP}}$: the total dry mass of the product, in kg or other mass unit.

Actual Recirculation of product at the EoL as energy, heat and fuels:

$$\mathbf{ARaEHF = \frac{am_{PtEHF}}{m_{TP}} \times 100} \quad \mathbf{(54)}$$

Where,

ARaEHF: the actual recirculation of product at the EoL as energy, heat and fuels, %;

$\mathbf{am_{PtEHF}}$: the actual (dry) mass of the product that is further utilised after the EoL to produce energy, heat and fuels, in kg or other mass unit.

Designed Recirculation of product at the EoL as useful utilisation in biosphere:

$$\mathbf{DRaUF = \frac{dm_{PtUF}}{m_{TP}} \times 100} \quad \mathbf{(55)}$$

Where,

DRaUF: the designed recirculation of product at the EoL as useful utilisation in biosphere, %;

$\mathbf{dm_{PtUF}}$: the designed (dry) mass of the product that can be further utilised after the EoL as useful utilisation in biosphere, in kg or other mass unit;

$\mathbf{m_{TP}}$: the total dry mass of the product, in kg or other mass unit.

Actual Recirculation of product at the EoL as useful utilisation in biosphere:

$$\mathbf{ARaUF} = \frac{\mathbf{am_{PtUF}}}{\mathbf{m_{TP}}} \times \mathbf{100} \quad \mathbf{(56)}$$

Where,

ARaUF: the actual recirculation of product at the EoL as useful utilisation in biosphere, %;

am_{PtUF}: the actual (dry) mass of the product that is further utilised after the EoL as useful utilisation in biosphere, in kg or other mass unit.

4.1.5 Hazardous Substances Reporting

All actors of the supply chain need to report potential presence of hazardous substances in their feedstock(s) used, product(s) and by-product(s) generated, as well as process-function chemical(s) and other material(s) used in the production process of the product, using Tables 5-7. Primary producers should complete Tables 6 and 7.

Table 5: Hazardous Substances Reporting for Feedstock

Name of Feedstock	Hazardous Substances			
	Presence of Hazardous Substance in Feedstock	Verification of Hazardous Substance's Presence	List of Present or Potential Hazardous Substances	Weight Fraction of Hazardous Substance (%)
Feedstock X	i) Yes, ii) No, iii) Unknown	i) measured and certified or verified by a third party, ii) measured but not certified / verified by a third party, iii) not measured	Hazardous substance 1	
			Hazardous substance 2	
			Hazardous substance X	
Feedstock Y	i) Yes, ii) No, iii) Unknown	i) measured and certified or verified by a third party, ii) measured but not certified / verified by a third party, iii) not measured	Hazardous substance 1	
			Hazardous substance 2	
			Hazardous substance X	
Feedstock Z	i) Yes, ii) No,	i) measured and certified or verified by a third party,	Hazardous substance 1	

	iii) Unknown	ii) measured but not certified / verified by a third party, iii) not measured	Hazardous substance 2	
			Hazardous substance X	

Table 6: Hazardous Substances Reporting for Product(s) and By-Product(s)

		Hazardous Substances		
Name of Product	Presence of Hazardous Substance in Product	Verification of Hazardous Substance's Presence	List of Present or Potential Hazardous Substances	Weight Fraction of Hazardous Substance (%)
Product X	i) Yes, ii) No, iii) Unknown	i) measured and certified or verified by a third party, ii) measured but not certified / verified by a third party, iii) not measured	Hazardous substance 1	
			Hazardous substance 2	
			Hazardous substance X	
By-Product X.Y	i) Yes, ii) No, iii) Unknown	i) measured and certified or verified by a third party, ii) measured but not certified / verified by a third party, iii) not measured	Hazardous substance 1	
			Hazardous substance 2	
			Hazardous substance X	
By-Product X.Z	i) Yes, ii) No, iii) Unknown	i) measured and certified or verified by a third party, ii) measured but not certified / verified by a third party, iii) not measured	Hazardous substance 1	
			Hazardous substance 2	
			Hazardous substance X	

Table 7: Hazardous Substances Reporting for Process-Function Chemical(s) and other Material(s)

Name of each process chemical / material	CAS number of each process chemical / material	Certification for biodegradability or other	Presence of Hazardous Substance	List of Present or Potential Hazardous Substances
Process Chemical X	CAS	i) Yes, ii) No	i) Yes, ii) No	Hazardous substance 1
				Hazardous substance 2
				Hazardous substance X
Process Chemical Y	CAS	i) Yes, ii) No	i) Yes, ii) No	Hazardous substance 1
				Hazardous substance 2
				Hazardous substance X
Process Chemical Z	CAS	i) Yes, ii) No	i) Yes, ii) No	Hazardous substance 1
				Hazardous substance 2
				Hazardous substance X

4.2 Selected Circular Indicators & Do No Significant Harm Principle

This section examines the relationship between the selected indicators and the environmental objectives outlined in the EU Taxonomy Regulation and the Do No Significant Harm principles. The results of this analysis are summarized in Table 8, providing insights into the direct and indirect contributions of each indicator to not significantly harming climate change mitigation and adaptation, sustainable use and protection of water and marine resources, pollution prevention and control, and the protection and restoration of biodiversity and ecosystems. As the CE objectives of the indicators have already been analysed in depth, Table 8 does not provide detailed analysis of this aspect.

The selected indicators primarily focus on circularity measurement and assessment (i.e. environmental objective no. 4) but secondarily, they also target directly or indirectly some additional environmental objectives. For instance, indicators like the verified virgin renewable product percentage and the modified biomass utilization factor directly contribute to climate change mitigation by reducing greenhouse gas emissions through the use of renewable sources and biomass for energy. Similarly, the average renewable energy consumed in the total production process and energy intensity indicators also directly target climate change mitigation by promoting the use of renewable energy and reducing energy consumption, respectively.

Many of the indicators also indirectly contribute to other environmental objectives. For example, the circularity characterization factor of residues and reused content of products improve waste management and resource efficiency, thereby indirectly supporting climate change mitigation and the sustainable use of water resources. The designed and actual reusability of a product, along with refurbishing and remanufacturing indicators, promote longer product life and adaptability to changing conditions, indirectly supporting climate change adaptation.

However, for better clarity and direct measurement of all environmental objectives, additional environmental indicators need to be included. The selected indicators are effective for assessing circularity but do not comprehensively cover all the environmental objectives defined in the EU Taxonomy Regulation and the Do No Significant Harm principles. Specifically, indicators directly measuring the condition and resilience of ecosystems, or the conservation status of habitats and species are limited. Therefore, to fully align with these environmental objectives, it is essential to incorporate additional indicators that provide direct measurement and assessment. Relevant indicators to measure the remaining objectives can be found in Deliverable 2.2, which offers a more comprehensive set of metrics to ensure holistic environmental performance assessment. This is also the approach taken by ISO59020, which provides a list of standardised metrics to assess the intrinsic circularity of resource flows, whilst emphasising the need for complementary sustainability analysis of consequential impacts.

Table 8: Relationship between Selected Indicators and Environmental Objectives of the EU Taxonomy Regulation

Selected Indicator	Climate Change Mitigation			Climate Change Adaptation			Sustainable Use & Protection of Water and Marine resources			CE	Pollution Prevention and Control			Protection & Restoration of Biodiversity & Ecosystems		
	Direct	Indirect	Explanation	Direct	Indirect	Explanation	Direct	Indirect	Explanation		Direct	Indirect	Explanation	Direct	Indirect	Explanation
Verified virgin renewable product (%)		X	Reduces GHG emissions by using renewable sources							X				X		Conserves the status of habitats and/or species by ensuring their renewability
Circularity characterisation factor of residue (%)		X	Improves waste management, reducing GHG emissions					X	Improves water quality by using waste, reducing expulsion to environmental sinks	X		X	Reduces pollution through efficient waste use		X	Conserves the status of habitats and/or species by using secondary sources
Modified Biomass Utilisation Factor		X	The use of biomass for energy reduces fossil fuel dependence							X		X	Reduces emissions through better biomass management		X	Conserves the status of habitats and/or species by using secondary sources
Value-based Biomass Utilisation Factor										X						
Reused content of product (%)		X	Reduces demand for new raw materials, indirectly reducing GHG emissions							X					X	Conserves the status of habitats and/or species by using secondary sources
Pre-consumer recycled bio-based content of product (%)		X	Reduces demand for new bio-based materials, indirectly reducing GHG emissions							X					X	Conserves the status of habitats and/or species by using secondary sources
Pre-consumer recycled fossil-based		X	Reduces demand for new fossil-based materials,							X						

content of product (%)			indirectly reducing GHG emissions													
Post-consumer recycled content of product (%)		X	Reduces demand for new materials, indirectly reducing GHG emissions							X		X	Reduces pollution through efficient waste utilization		X	Conserves the status of habitats and/or species by using secondary sources
Virgin renewable content of product (%)	X		Reduces GHG emissions by using renewable sources							X						
Content of Primary Producers' Circular Residue in Product (%)		X	Utilizes residues, indirectly reducing GHG emissions							X		X	Reduces pollution through efficient waste utilization		X	Conserves the status of habitats and/or species by using secondary sources
Circularity characterisation factor of (bio-based) by-product (%)		X	Utilizes by-products, indirectly reducing GHG emissions							X		X	Reduces pollution by minimizing wasted resources			
Average renewable energy consumed in the total production process for the generated product (%)	X		Reduces GHG emissions by using renewable energy							X		X	Use of renewable energy sources indirectly reduces pollution			Conserves the status of habitats and/or species by ensuring their renewability
Energy Intensity to produce the product	X		Reduces GHG emissions by using less energy													
Energy Intensity performance in comparison to industry	X		Reduces GHG emissions by using less energy													

average																
Circular water withdrawal for the total production process for the generated product (%)							X		Promotes sustainable water use	X					X	Maintains water for ecosystem functioning
Circular water discharge for the total production process for the generated product (%)							X		Promotes sustainable water use	X	X		Ensures appropriate water quality of discharges		X	Provides water for ecosystem functioning
Internal water recirculation or reuse in the total production process of the product							X		Promotes sustainable water use	X						
Water Intensity to produce the product							X		Promotes sustainable water use							
Water Intensity performance in comparison to industry average							X		Promotes sustainable water use							
Circular process-function chemical(s)/material(s) input										X		X	Circular sourcing of process-function materials reduced			

for the total production process of the generated product (%)													chemical wastage			
Process-function chemical(s)/material(s) Intensity to produce the product		X	Reduces chemical use, lowering GHG emissions													
Process-function chemical(s)/material(s) Intensity performance in comparison to industry average		X	Reduces chemical use, lowering GHG emissions													
Average Lifetime of product in comparison to industry average		X	Reduces need for new products, indirectly lowering GHG emissions		X	Longer product life adapts to changing conditions				X		X	Reduces rate of resource disposal			
Designed reusability of a product (%)		X	Promotes reuse, indirectly reducing GHG emissions		X	Reusable design adapts to changing conditions				X						
Actual reusability of a product (%)		X	Reduces need for new products, indirectly lowering GHG emissions		X	Actual reuse adapts to changing conditions				X		X	Reduces rate of resource disposal			
Designed refurbishing and remanufacturing of a		X	Refurbishing reduces need for new products, indirectly		X	Refurbishing adapts to changing conditions				X						

product (%)			lowering GHG emissions													
Actual refurbishing and remanufacturing of a product (%)		X	Remanufacturing reduces need for new products, indirectly lowering GHG emissions		X	Remanufacturing adapts to changing conditions				X		X	Reduces rate of resource disposal			
Designed Recirculation of product at the EoL as pharmaceutical and fine chemical (%)		X	Recirculation reduces waste, indirectly lowering GHG emissions		X	Recirculation adapts to changing conditions				X						
Actual Recirculation of product at the EoL as pharmaceutical and fine chemical (%)		X	Recirculation reduces waste, indirectly lowering GHG emissions		X	Recirculation adapts to changing conditions				X		X	Reduces rate of resource disposal			
Designed Recirculation of product at the EoL as food and feed (%)		X	Recirculation reduces waste, indirectly lowering GHG emissions		X	Recirculation adapts to changing conditions				X						
Actual Recirculation of product at the EoL as food and feed (%)		X	Recirculation reduces waste, indirectly lowering GHG emissions		X	Recirculation adapts to changing conditions				X		X	Reduces rate of resource disposal			
Designed Recirculation of product at the EoL as bioplastics and polymers (%)		X	Recirculation reduces waste, indirectly lowering GHG emissions		X	Recirculation adapts to changing conditions				X						

Actual Recirculation of product at the EoL as bioplastics and polymers (%)		X	Recirculation reduces waste, indirectly lowering GHG emissions		X	Recirculation adapts to changing conditions				X		X	Reduces rate of resource disposal			
Designed Recirculation of product at the EoL as bulk chemicals and materials (%)		X	Recirculation reduces waste, indirectly lowering GHG emissions		X	Recirculation adapts to changing conditions				X						
Actual Recirculation of product at the EoL as bulk chemicals and materials (%)		X	Recirculation reduces waste, indirectly lowering GHG emissions		X	Recirculation adapts to changing conditions				X		X	Reduces rate of resource disposal			
Designed Recirculation of product at the EoL as energy heat and fuels (%)		X	Recirculation reduces waste, indirectly lowering GHG emissions		X	Recirculation adapts to changing conditions				X						
Actual Recirculation of product at the EoL as energy heat and fuels (%)		X	Recirculation reduces waste, indirectly lowering GHG emissions		X	Recirculation adapts to changing conditions				X						
Designed Recirculation of product at the EoL as useful utilisation		X	Recirculation reduces waste, indirectly lowering GHG emissions		X	Recirculation adapts to changing conditions				X						

in biosphere (%)																
Actual Recirculation of product at the EoL as useful utilisation in biosphere (%)		X	Recirculation reduces waste, indirectly lowering GHG emissions		X	Recirculation adapts to changing conditions				X						

4.3 Potential Gaps of Selected Circular Indicators & Further Developments

Efforts to develop circularity indicators have predominantly concentrated on material inputs, including the appropriate characterization of feedstocks and bio-based products, and on circular production indicators. These efforts are critical for ensuring that bio-based sectors adopt sustainable practices. Additionally, specific focus has been given to addressing certain unique characteristics of the bio-based sector, such as cascading use via co-production, which ensures the efficient utilization of biomass and other bio-based materials.

However, despite the comprehensive nature of these indicators, several potential gaps remain that require further development to fully capture the essence of circularity. One significant gap is the need for enhanced use phase and end-of-life (EoL) indicators. While current indicators do consider the whole lifecycle of bio-based products, they may not be sufficiently advanced to address all the nuances of the use phase and EoL stages. These stages are crucial for ensuring that products remain within the CE for as long as possible, thereby maximizing their utility and minimizing waste. Consecutive uses can change the quality and quantity of recycled materials, a factor not adequately addressed by current indicators.

The current indicators have successfully integrated hazardous substances reporting, recognizing the importance of monitoring and controlling hazardous materials within bio-based products. However, further advancements are needed to minimize the risk of hazardous substances accumulating within the CE. This is crucial because even small amounts of hazardous substances can have significant long-term impacts on human health and the environment. Ensuring rigorous reporting and monitoring, along with developing safer alternatives, can help mitigate these risks.

While the use of renewable resources has been emphasized, there is a need for including indicators measuring the efficiency of replacing non-renewable resources with renewable ones. This is important because bio-based inputs often require a higher quantity to produce the same amount of products compared to fossil-based inputs.

Indicators that measure the impact of bio-based products on the regeneration of natural systems are essential. Although this deliverable covers ensuring and verifying the renewability of input resources, as well as the safe return of bio-based products to the biosphere for useful utilization, further advancements are needed focusing on measuring the actual impacts and benefits. These indicators should evaluate how the production and disposal of bio-based products affect soil health, water quality, and biodiversity. Ensuring that bio-based products contribute to, rather than detract from, the regeneration of natural systems is crucial for sustainability.

Moreover, indicators measuring the efficiency of resource use across different stages of the product lifecycle are needed. These indicators should assess how effectively resources are utilized during manufacturing, the efficiency of converting inputs into final products, and the effectiveness of recycling and reuse processes. This comprehensive approach would provide a more complete understanding of resource efficiency.

In conclusion, while significant progress has been made in developing circularity indicators for the bio-based sector, there are still several gaps that need to be addressed. Enhancing use phase and EoL indicators, improving hazardous substances reporting, and developing new indicators to measure the efficiency of resource use, the regeneration of natural systems, and the recirculation and utility of materials are essential steps towards achieving a truly CE. By addressing these gaps, we can ensure that the bio-based sector contributes positively to environmental sustainability and resource efficiency. This will require ongoing innovation and collaboration among stakeholders to develop and implement more comprehensive and effective circularity indicators.

5 Link Circularity and Sustainability Indicators

Circularity indicators are broadly categorized into two types: intrinsic circularity and consequential circularity (i.e., sustainability impacts and values). The focus of this deliverable is the selection of intrinsic circularity indicators to avoid replicating the work developed and described in Deliverable 2.2, which addresses the definition of criteria and sustainability indicators.

Intrinsic circularity indicators measure the circularity within a system by evaluating resource flows, resource value, and circular actions. These indicators help to assess how well a system retains value through reuse, recycling, and resource efficiency. Key elements include the inflow and outflow of resources, the added, retained, or lost value of materials, and the efficiency of circular actions such as recycling and resource recovery. By focusing on these aspects, intrinsic indicators provide insights into the internal mechanics of circularity, ensuring resources are utilized optimally within a closed-loop system.

Consequential circularity indicators, on the other hand, assess the broader sustainability impacts of circular practices. These indicators measure environmental, economic, and social outcomes resulting from implementing circular strategies. They ensure that circular practices contribute positively to overall sustainability and do not lead to unintended negative consequences.

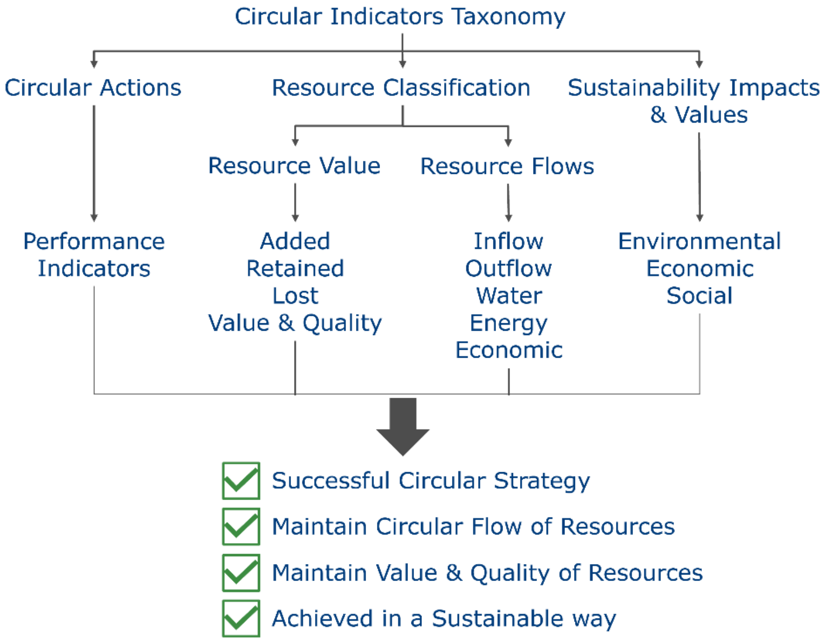

Figure 4: Holistic circularity indicator taxonomy based on the ISO 59020

Figure 4 illustrates the taxonomy of circular indicators, divided into three main categories: Circular Actions, Resource Classification, and Sustainability Impacts & Values. Circular Actions include performance indicators that measure the effectiveness of actions taken to maintain circularity, such as recycling rates and resource recovery efficiency. Resource Classification is further divided into Resource Value and Resource Flows. Resource Value focuses on the added, retained, and lost value and quality of resources within the CE, while Resource Flows include inflows and outflows of materials, energy, water, and economic resources, essential for maintaining a circular flow within the system. Sustainability Impacts & Values evaluate the environmental, economic, and social impacts of circular practices, ensuring they contribute positively to sustainability. The successful circular strategy lies at the intersection of these categories, maintaining the circular flow of resources, retaining their value and quality, and achieving these goals sustainably.

While intrinsic circularity indicators are crucial for understanding how well a system retains and recycles resources, they do not necessarily guarantee positive sustainability outcomes. For instance, a high recycling rate might reduce waste but could also lead to increased energy consumption and carbon emissions if the recycling process is inefficient or relies on non-renewable energy sources. This highlights the need for consequential circularity indicators to measure the broader impacts on the environment, economy, and society.

Intrinsic circularity indicators are necessary for several reasons. They provide insights into how efficiently resources are used and reused within a system, promoting better management and reduced waste. They also help identify areas for improving processes to enhance circularity, such as improving recycling technologies or increasing the use of renewable resources. Furthermore, they enable organizations to benchmark their circularity performance and report progress transparently.

Consequential circularity indicators are equally important. They ensure that circular practices contribute to overall sustainability goals, addressing potential trade-offs and negative impacts. These indicators provide a comprehensive assessment of the environmental, economic, and social impacts of circular practices, guiding decision-makers toward more sustainable solutions. Additionally, they help organizations align with sustainability policies and regulations, ensuring that circularity initiatives support broader sustainability agendas.

In conclusion, while the focus of this deliverable is on intrinsic circularity indicators, it is essential to measure both intrinsic and consequential circularity indicators to ensure that circular practices contribute positively to sustainability. Therefore, both frameworks in D2.2 and D2.3 will be integrated by into certification schemes by WP4 to ensure holistic and robust developments. The figure provided serves as a roadmap, highlighting the importance of maintaining circular resource flows, retaining resource value, and achieving these goals in a sustainable manner. By integrating both types of indicators, we can achieve a more comprehensive and effective evaluation of circular strategies using bio-based certification schemes, ultimately leading to more sustainable and resilient systems.

6 Conclusion

This deliverable of the BioReCer project focuses on developing and selecting circular indicators tailored specifically for bio-based products. The key message of this deliverable is the critical need to adapt CE principles to the unique characteristics of the bio-based sector. Traditional circularity indicators, primarily designed for technical and fossil-based systems, do not adequately address the complexities and lifecycle stages of bio-based products. This gap has hindered the bio-based industry's ability to monitor its circularity transition, demonstrate its advancements, and gain public and customer acceptance, which are crucial for economic incentives and sustainability.

The key outcomes of this deliverable include the identification and development of a comprehensive set of circular indicators that encompass the entire lifecycle of bio-based products. These indicators are designed to measure circularity from raw material extraction to end-of-life management, ensuring a holistic approach. The indicators cover various aspects of circularity and are categorized into material inputs, circular production, use phase, end-of-life (EoL) options, and hazardous substances reporting. These indicators are calculated differently for primary producers, pre-consumer producers, post-consumer producers, intermediate producers, and final producers, recognizing the distinct roles and impacts at each stage of the supply chain.

Primary Producers: These producers, such as forestry, agricultural, and fishery producers, generate raw bio-based materials. Indicators for primary producers focus on the sustainable and circular use of natural resources. This includes material input indicators that assess the verified virgin renewable content and the circularity characterization factor of residues. These indicators ensure that primary producers validate the renewability and sustainability of their feedstock and efficiently manage by-products and residues.

Pre-consumer Producers: Pre-consumer producers obtain their main feedstock from primary producers and other upstream actors. They include intermediate producers, such as pulp and paper industries and biorefineries, and final producers, like biofertilizer facilities. The circular indicators for these producers include material input characterization, such as the pre-consumer recycled content of products and the circularity characterization factor of received residues. These indicators ensure that pre-consumer producers can trace their feedstock back to primary production and validate its circularity.

Post-consumer Producers: These producers handle materials after their initial use phase. They include recyclers and remanufacturers. Post-consumer producers must calculate indicators starting with the input received from the consumer phase, which includes post-consumer recycled content and the circularity characterization factor of post-consumer by-products. This approach acknowledges the complexity of mixed and transformed biomass feedstocks at this stage.

Intermediate Producers: Intermediate producers provide essential feedstock for other industries. They include companies that generate products requiring further processing, such as composite wood producers using unconventional biomass streams, such as agricultural residues. Indicators for intermediate producers cover the entire lifecycle of their products, including material inputs, circular production, use phase, and EoL options. However, intermediate producers provide EoL indicators based on their designed capabilities and product specificities and composition. This ensures that intermediate producers manage their resources efficiently and contribute to the CE by promoting cascading use.

Final Producers: Final producers generate the end product that is directly provided to the user or consumer, and in BioReCer include biofertilizer facilities that produce soil amendments for agricultural use. Indicators for final producers include all aspects of circularity measurement: material inputs, circular production, use phase, and EoL options. Unlike intermediate producers, final producers provide actual EoL indicators, reflecting the real-world end-of-life outcomes of their products. These indicators ensure that final producers manage their products' entire lifecycle, from production to disposal, promoting sustainability and circularity.

A significant emphasis of the project is distinguishing between intrinsic and consequential circularity indicators. Intrinsic indicators measure the inherent circularity qualities of products and processes, such as recyclability, durability, and renewable content. Consequential indicators, while addressed in Deliverable 2.2, measure the broader impacts and outcomes of circular practices, including environmental and economic sustainability outcomes. This deliverable focuses primarily on intrinsic circularity indicators to avoid duplicating efforts and ensure a comprehensive approach to circularity assessment. It is hoped this deliverable highlights the need for the development of certification schemes that combine circularity and sustainability dimensions, as mandated by standards such as ISO59020.

By developing these tailored circular indicators, the BioReCer project aims to fill the critical gap in current circularity assessments, providing the bio-based industry with the necessary tools to monitor and enhance its circularity practices. The integration of these indicators into certification schemes as part of D4.3 will enable the bio-based sector to verify its circularity claims officially, fostering greater customer trust and acceptance.

In summary, this deliverable has established a foundational framework for advancing circularity in the bio-based sector. The developed indicators provide a comprehensive approach to measuring circularity across the entire lifecycle of bio-based products, addressing the specific needs and challenges of the bio-based industry. These efforts support the transition towards a more sustainable and resilient CE, positioning the bio-based sector at the forefront of CE practices.

7 List of abbreviations

ALTRP	Average Lifetime of the Product
ARaBPP	Actual Recirculation of Product as Bioplastics and Polymers
ARaBCM	Actual Recirculation of Product as Bulk Chemicals and Materials
ARaEHF	Actual Recirculation of Product as Energy, Heat, and Fuels
ARaFF	Actual Recirculation of Product as Food and Feed
ARaPFC	Actual Recirculation of Product as Pharmaceutical and Fine Chemicals
ARaUF	Actual Recirculation of Product as Useful Utilization in Biosphere
AREUP	Actual Reusability of a Product
ARRP	Actual Refurbishing and Remanufacturing of a Product
BUE	Biomass Utilization Efficiency
BUF	Biomass Utilization Factor
Buind	Bioresource Utilization Index
CCF(R)	Circularity Characterisation Factor of Residue
CCF(BBB)n	Circularity Characterisation Factor of Pre-Consumer Bio-based By-Product
CCF(FBB)n	Circularity Characterisation Factor of Pre-Consumer Fossil-based By-Product
CCF(POB)n	Circularity Characterisation Factor of Post-Consumer By-Product
CCP	Circular Content of Product
CE	Circular Economy
CEI	Circular Economy Index
CET	Circular Economy Toolkit
CI	Circularity Index
Circ(T)	Circularity Indicator for Time-Weighted Material Efficiency
CM	Combination Matrix
CMT	Circularity Measurement Toolkit
CPI	Circularity Performance Indicator
CPFC/M	Circular Process-function Chemical(s)/Material(s) Input
CWW	Circular Water Withdrawal

CWD	Circular Water Discharge
DREUP	Designed Reusability of a Product
DRaBPP	Designed Recirculation of Product as Bioplastics and Polymers
DRaBCM	Designed Recirculation of Product as Bulk Chemicals and Materials
DRaEHF	Designed Recirculation of Product as Energy, Heat, and Fuels
DRaFF	Designed Recirculation of Product as Food and Feed
DRaPFC	Designed Recirculation of Product as Pharmaceutical and Fine Chemicals
DRaUF	Designed Recirculation of Product as Useful Utilization in Biosphere
DRRP	Designed Refurbishing and Remanufacturing of a Product
EI	Energy Intensity
EIP	Energy Intensity Performance
GRI	Global Resource Indicator
IWR	Internal Water Recirculation
LI	Longevity Indicator
MBUF	Modified Biomass Utilization Factor
MCI	Material Circularity Indicator
PCI	Product Circularity Indicator
PLCM	Product-Level Circularity Metric
PFC/MI	Process-function Chemical(s)/Material(s) Intensity
PFC/MIP	Process-function Chemical(s)/Material(s) Intensity Performance
PPRESC(P)	Content of Primary Producer’s Circular Residue in Product
PRRECBBC(P)	Pre-consumer Recycled Bio-based Content of Product
PRRECFBC(P)	Pre-consumer Recycled Fossil-based Content of Product
PORECC(P)	Post-consumer Recycled Content of Product
QC	Circularity of Material Quality
REC	Renewable Energy Consumed
REUC(P)	Reused Content of Product
RI	Recycling Indices
RPI	Reuse Potential Indicator
RBR	Recycling Benefit Ratio

RCBR	Recycling Carbon Benefit Ratio
SCI	Sustainable Circular Index
VBO(X)n+1	Value-added of Product/By-product X for the Next Actor
VEFn(t)	Total Production Efficiency in Producing Valuable Products and By-products
VMBUF	Value-based Biomass Utilization Factor
VRENC(P)	Virgin Renewable Content of Product
VVREN(P)	Verified Virgin Renewable Product
WIP	Water Intensity Performance
WI	Water Intensity
VRENC(P)	Virgin Renewable Content of Product

8 References

Adibi, N., Lafhaj, Z., Yehya, M., & Payet, J. (2017). Global Resource Indicator for life cycle impact assessment: Applied in wind turbine case study. Journal of Cleaner Production, 165, 1517–1528. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.07.226

Azevedo, S. G., Godina, R., & Matias, J. C. de O. (2017). Proposal of a Sustainable Circular Index for Manufacturing Companies. Resources, 6(4). https://doi.org/10.3390/resources6040063

Blomsma, F., & Tennant, M. (2020). CE: Preserving materials or products? Introducing the Resource States framework. Resources, Conservation and Recycling, 156, 104698. https://doi.org/https://doi.org/10.1016/j.resconrec.2020.104698

Bracquené, E., Dewulf, W., & Duflou, J. R. (2020). Measuring the performance of more circular complex product supply chains. Resources, Conservation and Recycling, 154, 104608. https://doi.org/https://doi.org/10.1016/j.resconrec.2019.104608

Cucciniello, R., & Anastas, P. T. (2021). Design for degradation or recycling for reuse? Current Opinion in Green and Sustainable Chemistry, 31, 100528. https://doi.org/https://doi.org/10.1016/j.cogsc.2021.100528

Cullen, J. M. (2017). CE: Theoretical Benchmark or Perpetual Motion Machine? Journal of Industrial Ecology, 21(3), 483–486. https://doi.org/https://doi.org/10.1111/jiec.12599

D'Amato, D., Droste, N., Allen, B., Kettunen, M., Lähtinen, K., Korhonen, J., Leskinen, P., Matthies, B. D., & Toppinen, A. (2017). Green, circular, bio economy: A comparative analysis of sustainability avenues. Journal of Cleaner Production, 168, 716–734. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.09.053

Di Maio, F., Rem, P. C., Baldé, K., & Polder, M. (2017a). Measuring resource efficiency and CE: A market value approach. Resources, Conservation and Recycling, 122, 163–171. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.02.009

Di Maio, F., Rem, P. C., Baldé, K., & Polder, M. (2017b). Measuring resource efficiency and CE: A market value approach. Resources, Conservation and Recycling, 122, 163–171. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.02.009

Ellen MacArthur Foundation. (2015). Material Circularity Indicator Methodology: An approach to measuring circularity.

Ellen MacArthur Foundation. (2019). Material Circularity Indicator Methodology: An approach to measuring circularity.

Evans, J., & Bocken, N. (2014). A tool for manufacturers to find opportunity in the CE – www.circulareconomytoolkit.org. SDM 2014, International Conference on Sustainable Design and Manufacturing.

Figge, F., Thorpe, A. S., Givry, P., Canning, L., & Franklin-Johnson, E. (2018). Longevity and Circularity as Indicators of Eco-Efficient Resource Use in the CE. Ecological

Economics, 150, 297–306. https://doi.org/https://doi.org/10.1016/j.ecolecon.2018.04.030

Franklin-Johnson, E., Figge, F., & Canning, L. (2016). Resource duration as a managerial indicator for CE performance. Journal of Cleaner Production, 133, 589–598. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.05.023

Garza-Reyes, J. A., Salomé Valls, A., Peter Nadeem, S., Anosike, A., & Kumar, V. (2019). A circularity measurement toolkit for manufacturing SMEs. International Journal of Production Research, 57(23), 7319–7343. https://doi.org/10.1080/00207543.2018.1559961

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on CE: the expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production, 114, 11–32. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.09.007

Hildebrandt, J., Bezama, A., & Thrän, D. (2017). Cascade use indicators for selected biopolymers: Are we aiming for the right solutions in the design for recycling of bio-based polymers? Waste Management & Research, 35(4), 367–378. https://doi.org/10.1177/0734242X16683445

Huysman, S., De Schaepmeester, J., Ragaert, K., Dewulf, J., & De Meester, S. (2017). Performance indicators for a CE: A case study on post-industrial plastic waste. Resources, Conservation and Recycling, 120, 46–54. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.01.013

Huysveld, S., Hubo, S., Ragaert, K., & Dewulf, J. (2019). Advancing CE benefit indicators and application on open-loop recycling of mixed and contaminated plastic waste fractions. Journal of Cleaner Production, 211, 1–13. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.11.110

Iffland, K., Sherwood, J., Carus, M., Raschka, A., Farmer, T., & Clark, J. (2015). Definition, Calculation and Comparison of the "Biomass Utilization Efficiencies (BUE)" of Various Bio-based Chemicals, Polymers and Fuels.

Korhonen, J., Nuur, C., Feldmann, A., & Birkie, S. E. (2018). CE as an essentially contested concept. Journal of Cleaner Production, 175, 544–552. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.12.111

Ladu, L., & Morone, P. (2021). Holistic approach in the evaluation of the sustainability of bio-based products: An Integrated Assessment Tool. Sustainable Production and Consumption, 28, 911-924e6. https://doi.org/https://doi.org/10.1016/j.spc.2021.07.006

Linder, M., Sarasini, S., & van Loon, P. (2017). A Metric for Quantifying Product-Level Circularity. Journal of Industrial Ecology, 21(3), 545–558. https://doi.org/https://doi.org/10.1111/jiec.12552

Lokesh, K., Matharu, A. S., Kookos, I. K., Ladakis, D., Koutinas, A., Morone, P., & Clark, J. (2020). Hybridised sustainability metrics for use in life cycle assessment of bio-based products: resource efficiency and circularity. Green Chemistry, 22(3), 803–813. https://doi.org/10.1039/C9GC02992C

Mantau, U. (2015). Wood flow analysis: Quantification of resource potentials, cascades and carbon effects. Biomass and Bioenergy, 79, 28–38. https://doi.org/https://doi.org/10.1016/j.biombioe.2014.08.013

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G. A., Alaerts, L., Van Acker, K., de Meester, S., & Dewulf, J. (2019). CE indicators: What do they measure? Resources, Conservation and Recycling, 146, 452–461. https://doi.org/https://doi.org/10.1016/j.resconrec.2019.03.045

Nelen, D., Manshoven, S., Peeters, J. R., Vanegas, P., D'Haese, N., & Vrancken, K. (2014). A multidimensional indicator set to assess the benefits of WEEE material recycling. Journal of Cleaner Production, 83, 305–316. https://doi.org/https://doi.org/10.1016/j.jclepro.2014.06.094

Park, J. Y., & Chertow, M. R. (2014). Establishing and testing the "reuse potential" indicator for managing wastes as resources. Journal of Environmental Management, 137, 45–53. https://doi.org/https://doi.org/10.1016/j.jenvman.2013.11.053

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

Razza, F., Briani, C., Breton, T., & Marazza, D. (2020). Metrics for quantifying the circularity of bioplastics: The case of bio-based and biodegradable mulch films. Resources, Conservation and Recycling, 159, 104753. https://doi.org/https://doi.org/10.1016/j.resconrec.2020.104753

Renfrew, D., Vasilaki, V., Nika, E., Tsalidis, G. A., Marin, E., & Katsou, E. (2024). Systematic assessment of wastewater resource circularity and sustainable value creation. Water Research, 251, 121141. https://doi.org/https://doi.org/10.1016/j.watres.2024.121141

Stegmann, P., Londo, M., & Junginger, M. (2020). The circular bioeconomy: Its elements and role in European bioeconomy clusters. Resources, Conservation & Recycling: X, 6, 100029. https://doi.org/https://doi.org/10.1016/j.rcrx.2019.100029

Steinmann, Z. J. N., Huijbregts, M. A. J., & Reijnders, L. (2019). How to define the quality of materials in a CE? Resources, Conservation and Recycling, 141, 362–363. https://doi.org/https://doi.org/10.1016/j.resconrec.2018.10.040

Vamza, I., Kubule, A., Zihare, L., Valters, K., & Blumberga, D. (2021). Bioresource utilization index – A way to quantify and compare resource efficiency in production. Journal of Cleaner Production, 320, 128791. https://doi.org/https://doi.org/10.1016/j.jclepro.2021.128791

van Schaik, A., & Markus A. Reuter. (2016). Recycling Indices Visualizing the Performance of the CE. World of Metallurgy , 69(4).

vom Berg, C., Carus, M., Piltz, G., Dammer, L., Breitmayer, E., & Essel, R. (2022). The Biomass Utilisation Factor (BUF).

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

White, E., & Oldfield, T. (2016). Report on the holistic analysis of AWCB chains and logistics of AWCB valorisation systems (Deliverable No. 1.3). AgroCycle Project (Grant Agreement No. 690142). NUID UCD. Retrieved from www.AgroCycle.eu