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Biocircularity: A Yardstick to Assess the Impact of Circular Bioeconomy

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14.1 Introduction

The concepts of circular economy (ECDGE, 2020) and bioeconomy (EC, 2022) have emerged as cornerstones of European Union "sustainability" policies. Circular economy should theoretically decouple adverse impact from consumption while maintaining economic activity, and bioeconomy should reduce dependence on fossil carbon by substituting biogenic carbon. The most recent policy has integrated both into the concept of circular bioeconomy (EC, 2025), theoretically providing decarbonisation and decoupling in one policy context. While these policies have theoretical benefits for European society and the wider world, there are many issues that make implementation of a transition from a fossil fuel driven linear economy to circular bioeconomy a complex challenge. An important question for many stakeholders, including research funders, investors, scientists, policy makers and consumers, is, how to evaluate whether an innovation or system that delivers a product to market (purchased by a business (B2B) or consumer (B2C)) is contributing to a sustainable future.

This chapter starts by setting the context of circular bioeconomy, presents a framework that can be used to objectively assess whether a product or process contributes to a sustainable circular bioeconomy, and then evaluates

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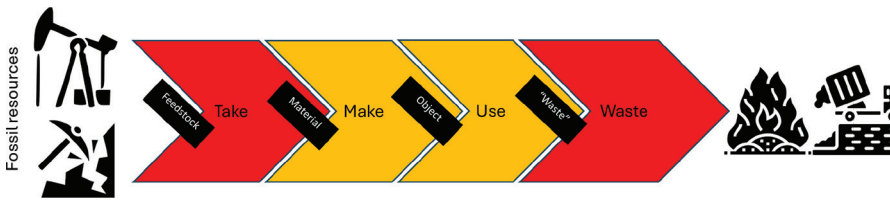

Figure 14.1 Schematic representation of the conventional, fossil fuel driven economy. Source: drawn by the author.

how the framework could be used to help identify best practice, protect consumers from greenwash and help product selection choices, and provide a basis for new product design. It concludes with a brief evaluation of how biocircularity could contribute to achieving sustainable development goal targets.

14.1.1 Circular economy, bioeconomy and circular bioeconomy

In very simple terms, the circular economy concept is intended to decouple environmental impact from consumption. Over the last 200 years, industrial development and growth have been founded on a 'take-make-use-waste' approach (Figure 14.1). It is now apparent that excessive waste, polluting emissions and energy and scarcity of resources have been driven by economic growth causing adverse impacts such as climate change, water quality loss and biodiversity loss, and adverse human and ecosystem outcomes (Ripple et al., 2017). The linear conception of economic development arose in the early 20th century when human populations were much smaller and natural resources much more abundant. The linear, growth economy assumes that resources are replaceable or so vast they will never run out, that it is cheaper to dispose and start again than to repair, reuse or recover materials, and that prosperity and happiness are driven by consumption of things. The linear economy extracts value and profit by the continual sale of newer, more fashionable products.

The European Union has now recognised that natural resources are finite, and earth systems cannot adapt to and buffer the impact of the global economy. One policy response has been to look to bioeconomy as a solution. The European Community originally described the bioeconomy as, "… all sectors and systems that rely on biological resources…, their functions and principles [including] land and marine ecosystems and the services they provide…all economic and industrial sectors that use biological resources and processes…" (EU, 2018). This is a general definition that is inclusive of many actor and stakeholder perspectives and offers little disruption

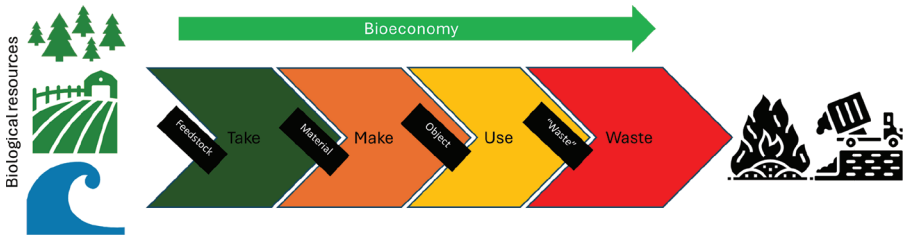

Figure 14.2 Business-as-usual conception of linear bioeconomy substituting biogenic carbon for fossil carbon in materials and products. Source: drawn by the author.

of business-as-usual other than a slight emphasis on ecosystem services (Figure 14.2). It does not really help stakeholders understand the attributes of bioeconomy that are necessary to change the carbon intensive, take-make-use-waste business-as-usual. The ambition is for bioeconomy to be an alternative way of delivering the products, processes, and services wanted by human society that are less reliant on fossil carbon, for example, the harnessing of biological processes such as fermentation to supply materials such as monomers and polymers built from biogenic carbon to make products such as plastic bottles, and to deliver services such as soil reclamation using microbes (Laibach et al., 2019).

Despite this very techno-centric description of bioeconomy, it has a familiarity for consumers because for centuries we have relied on it for food, fibre, provided building materials, medicines and some raw materials for industry. The past century and more of industrial revolution has reshaped the economy through use of non-renewable resources and fossil carbon (Zilberman et al., 2018). For example, it is difficult to image 20th Century agriculture without motive power enabled by oil. In recent years there has been an increased focus on reversing this trajectory; returning to a reliance on biology, rather than oil and mined minerals to create materials to make everyday objects, provide chemicals and energy for movement, heating, and lighting. Bioeconomy conceived in this way will not necessarily eliminate polluting emissions to the wider environment that have an adverse impact on human wellbeing (human capital), natural resources (and the broader concept of the stocks, processes and flows of services provided by natural capital), and the man-made environment (cities, roads and other infrastructure), but it does offer a route to decarbonisation.

The European Unions has also embraced the circular economy as a policy strategy that can drive climate adaptation and reduce the impact of the economy on the natural environment. Circular economy takes a different approach to the traditional linear economies illustrated in Figures 14.1 and

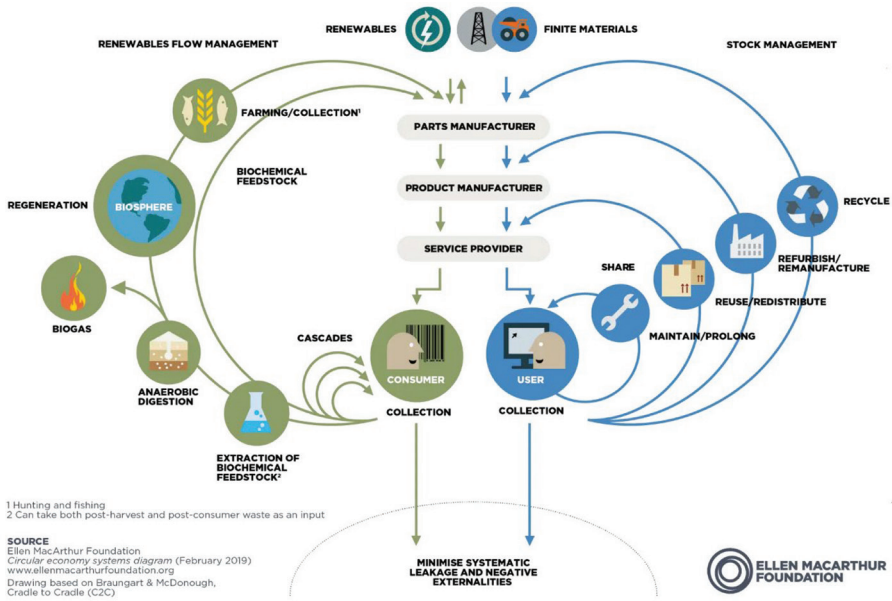

Figure 14.3 Schematic representation of the circular economy illustrating the technical cycle (blue) and the regenerative cycle (green). Source: Ellen MacArthur Foundation (2019).

14.2, where materials, goods and products are used for as long as possible and value and profit are extracted from the supply of materials that maintain their life through design for longevity, re-use, recycling and end of life resource extraction and return (Muñoz et al., 2024) (Figure 14.3). Circular economy should allow people to keep having the things they want, drive economic activity all while recognising that resources are finite and should not be wasted. A circular economy keeps the added value in products for as long as possible and aims to eliminate waste, keep resources within the economy when a product has reached the end of its life, so that they can be productively used again and again and hence create further value (Ellen MacArthur Foundation, 2015). The idea is that once a resource is extracted from the Earth to make something of value to humans, it is kept available for as long as possible until it has degraded so much that it can no longer be used, at which point any remaining resources or energy can be extracted and what is left is returned to the Earth. Theoretically the circular economy approach will decouple consumption from adverse environmental impact without compromising economic activity.

A sustainable circular bioeconomy should operate within the requirements of the circular economy. A circular bioeconomy is not as simple as it sounds. A bioeconomy value chain may be spread across the world. For example, Irish milk production systems use feed from Brazil, Ukraine and Ireland. The milk is produced in Ireland and goes on to make milk powder and bioplastic containers in Ireland that travel to China. Here the milk powder is consumed and ends up in the sewerage system and a human, and the container ends up in a landfill or being composted and land spread somewhere near the city it was purchased in. In this case, we have to ask how circular can the *product* system really be? Obviously, the dairy product cannot be circularised. However, the circular bioeconomy also considers a regenerative cycle (Ellen MacArthur Foundation (2019)) (Figure 14.3). At a global scale, it is possible to envisage that some of the nutrients end up back in soil after time and many end-up in the oceans so becoming economically inaccessible for humans for centuries. At a local scale, it is almost inconceivable that the nutrient resource extracted from soil in Brazil or Ukraine will be returned through the circulation of the materials grown there. Another issue is the spatial distribution of people, and their demand for particular ecosystem services, which typically does not match the spatial distribution of the biosphere's capacity to supply those services. This raises the question of whether defining 'circular bioeconomy' without considering geography and scale is meaningful?

Another important question for circular bioeconomy is how long does something remain as a biomaterial? Coal is not regarded as a biomaterial despite being of biological origin. If a similar question is asked about lactic acid from biorefined waste streams e.g., whey permeate), the first time the plastic is used it is a bioeconomy product. If it is reused with minimal processing or energy input, presumably it remains a bioeconomy product, but if it is reprocessed following recycling to make a component of another object, does it still count as a part of the bioeconomy? It would certainly be part of the circular economy, so should be part of a circular bioeconomy. This raises the question, how much 'bio' is needed for something to be part of the bioeconomy (e.g., EuropeanBioplastis, 2016) and how distant from its biological origin does it have to travel to cease to be part of it? Measurements of the bioeconomy typically rely on economic metrics that approximate the share of "bio" in a particular sector in relation to its overall value or simply discount those economic areas deemed not "bio" enough (Ronzon et al., 2017; Wesseler and von Braun, 2017). Designing better metrics and indicators of bioeconomic growth and success are called for that are more economically precise but also broader than conventional economic value (El-Chickakli et al., 2016).

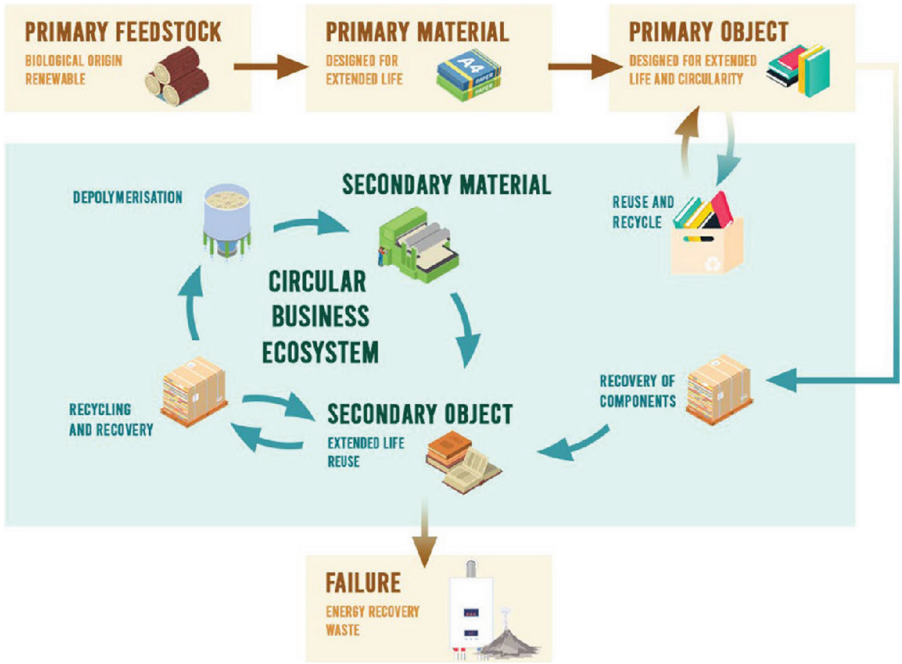

Figure 14.4 The Biocircularity Framework for evaluating whether a product of the circular bioeconomy is likely to be contributing to transition to a sustainable status. Source Holden et al. (2022).

14.2 Biocircularity: A Framework to Evaluate a Circular Bioeconomy Product

Biocircularity was developed as an unambiguous means of evaluating whether a circular bioeconomy system that creates materials and products is likely to offer the theoretical benefits of reduced environmental impact (circular economy) and decarbonisation (bioeconomy) (Holden et al., 2022). There are six attributes that are considered during the evaluation; their relationship is described in Figure 14.4. At present only five can be classified or quantified, and in practice it is currently not possible to use the framework as a yardstick or test of contribution to sustainable status, but even if it is used in a qualitative manner, the framing is still potentially useful for helping stakeholders evaluate and gain confidence in circular bioeconomy products. Each attribute of biocircularity will be considered in turn below.

1. **The primary feedstock**. This is the raw material that is used to create the primary material and products the system delivers. In conventional

economy over the last century or more, oil has been one of the most important feedstocks, along with a wide array of minerals. For a product to be the output of a sustainable circular bioeconomy, the feedstock must be of biological origin, thus the carbon is biogenic. It is possible that the energy used to support the growth of the feedstock will rely on fossil carbon, but the feedstock resource should be biological. The criterion of having been alive can be used to classify feedstocks.

2. **Renewability**. The feedstock should be renewable, meaning it can be harvested and regrow, year after year. Agricultural crops are often considered renewable because they can be grown over-and-over, again. This is typically true for short periods, perhaps measured in decades, but it is not unending. To ensure feedstock is genuinely renewable, the *ideal* would be to utilise a feedstock that does not deplete natural capital when it is grown. This means the resource is not produced at the expense of other ecosystem attributes such as biodiversity, soil health, water processing, environmental buffering and so on. There are many environmental metrics and natural capital accounting methods that can be used to quantify this attribute.

3. **Primary materials made for extended life**. The primary material created from the feedstock should be designed for longevity rather than decomposition, and its processes should, as far as possible, be driven by renewable energy. While much research has focused on biodegradable biomaterials (e.g., packaging materials), this is contrary to the goal of circular economy and will drive pressure on primary feedstocks. Biomaterials need to be designed for longevity in order to decouple use from production of primary feedstocks. The more this is decoupled, the more likely it is that feedstocks can be grown renewably, i.e., not at the expense of depleting natural capital. There are several resource use efficiency metrics that can be used at the feedstock/material scale (Lokesh et al., 2020) and the corporate scale (Bergmann et al., 2017) to quantify this attribute.

4. **Objects (useful product) designed for extended life and circularity**. An object designed for longevity, repurposing, reuse, subsequent material recovery and ultimately circulation of the material and its components (monomers, polymers, composites) will provide the maximum decoupling of impact and use. Manufacture and distribution using renewable energy should be prioritised. While there are methods such as “design for sustainability” (e.g., Ceschin and Gaziulusoy, 2016) and

mass and energy flow accounting methods (Kullmann et al., 2021), these will need to be coupled with repairability (Alarcón et al., 2021) and recyclability (Villalba et al., 2002) indexes to quantify this attribute if a circular bioeconomy product.

5. **Circular business ecosystem.** The current arrangement, or system, of businesses, service providers, retailer and consumers has developed in response to the take-make-use-waste linear economy, the success of which relies on growth (i.e., ever more sales, causing ever more impact in the world). There is very little understanding of what a circular business ecosystem should look like, and how to accelerate the transition towards such system. For instance, the plastic recycling scheme recently introduced in Ireland (The ReTurn Scheme) appears on the face-of-it to be a well organised arrangement to encourage circulation of plastics (https://re-turn.ie/). However, in the context of circular bioeconomy (and even just circular economy) it is not clear whether the business ecosystem required exists. Firstly, there is no separation of biobased and fossil carbon plastics. This is not critical, unless the quality of plastic determines its circulation pathway. Secondly, there is a very limited market for the recovered plastic (EPA, 2025). It remains unclear where recovered plastic is processed, but recent Circular Gap report suggests very little circulates (https://dashboard.circularity-gap.world/report/ireland/overview). As with other attributes in the framework, the business ecosystem should maximise utilisation of renewable energy. It is theoretically possible to quantify the interconnectedness and circulation of material through the business ecosystem, but an agreed metric for this attribute remains elusive.

6. **Avoid the failure of end of life**. For a circular economy to be successful, materials, components and products must remain in circulation in the Technosphere for as long as possible. In addition, suitable resources to drive a regenerative cycle through the soil also have to be utilised. The landfilling and incineration of materials should be avoided for as long as possible to maximise decoupling of impact and use. It is possible to record all biobased materials that end up in landfill or being incinerated, so this attribute is theoretically quantifiable.

14.3 Potential Role for the Biocircularity Framework

The biocircularity framework was developed for two purposes, both initially somewhat remote from the consumer, but both play an important role in bringing

biobased products to the market and making them available to consumers. Both purposes need to be recognised before addressing consumer issues.

The original context of biocircularity was researchers in the BiOrbioc Bioeconomy Research Ireland Centre having very different understanding of bioeconomy and circular economy (which reflects a similar lack of knowledge and collective understanding in wider society). Points-of-view ranged for thinking that any use of biomass was going to help make the world "more sustainable" to a view that the processing of fossil resources using biological methods should fall under the umbrella of bioeconomy. The (probably manufactured) uncertainty about the meaning of the word "sustainable", lack of thought about what bioeconomy really is, and simply not thinking about scientific niches in the context of wider society was causing misunderstanding, lack of coherent ethos and potentially contradictory messaging. The framework was designed to provide a coherent concept that could be the focus for conversation and debate (not necessarily agreement). As noted by Virgolino and Holden (2026), because of its relative youth, bioeconomy is very dependent on early-stage researchers for its innovations and developments, so some progress towards a coherent understanding by researchers was regarded as essential if the value of their work was to be conveyed to, and understood by, consumers.

The second context that emerged was to provide funders (of research) and investors (in commercial ventures) with a means of assessing claims made about research proposals and investment opportunities. Any research or commercial innovation that uses bioresources as the feedstock, whether that be precision bioreactors, novel plastics, biomolecule prospecting, food waste utilisation and so on, has tended to be placed in the context of global, regional and national sustainability-related policies. Many claims have been made about novel technologies that will be "more sustainable" and the potential for market transformation (Talwar and Holden, 2022). What became apparent to BiOrbic Bioeconomy Centre researchers was the lack of any framework against which such claims could be tested. There are examples of frameworks that address related questions, such as the addition of Sustainability Level (Vinnova, 2019) (Figure 14.5) to the Innovation Readiness Framework (https://kthinnovationreadinesslevel.com/). However, this welcome addition does not provide metrics and measures that can be used for quantitative assessment. Questions about contribution to real-world impacts, and frameworks such as the sustainable development goals require an additional consideration such as biocircularity. It should be clear from the context above, that the biocircularity framework offers a means of supporting new product design. If research funders and investors have a means to prioritise how money is used



Figure 14.5 The sutstainabiliy readiness lever framework that can be used by investors to assess sustainabililty contribution of a new venture. Source VINNAVO SISP(CC BY).

to support new commercial ventures, then innovators and entrepreneurs will have a motivation to design new products that benefit from, and drive, circular bioeconomy. The motivation to develop not only new, better products, but also the business ecosystems necessary to benefit from biocircular design could be a significant driver of economic activity, that compensates for the potential consequences of reducing demand driven economic growth. If circular bioeconomy products emerge from research and innovation is financially encouraged to consider biocircularity, consumers will be able to make better decisions with confidence.

From a consumer perspective, the biocircularity framework has the potential to provide a basis for protection against greenwash. There is little public understanding of what circular bioeconomy means, and the implications of the phrase when attached to a product. Associating a product with the bioeconomy (implying the use of biogenic carbon rather than fossil carbon) and with circular economy (implying decoupling of impact from consumption) has little meaning unless the consumer is aware of what the concepts mean and how they can be measured. There are three aspects of the framework that are particularly important for consumers to get to grips with. The first aspect, the biobased feedstock, ensuring biogenic carbon in products is a technical concept that does not necessarily have to be understood but should be verifiable.

The second concept, the renewability of the feedstock, which probably means little to the average consumer, is however critical for consumer confidence. Taking plastic use in the European Union as an extreme hypothetical example, it is easy to illustrate why the renewability criterion is so important. Using public data, the European Union consumed 56.5 million tonnes of plastic in 2020. On average, about 0.5 ha is required to grow the biomass needed to produce 1 t bioplastic. This means the European Union would require an area of 1.13 million km^2 to produce 1 year's demand for plastic, or an area the size of Scandinavia (Figure 14.6A). If an area of that size was managed for biomass feedstock (e.g., tree plantations) and then depleted of biomass in a short period of time, the consequences for ecosystem services and functions could be devastating (Power 2010). A further simple calculation, assuming it takes 60 years for a tree to regrow to be harvested, suggests the European Union would require 67.8M km^2 to produce the plastic it demands on an ongoing basis. Thus 5.6% of the world's population would require 45% of terrestrial land area of earth (Figure 14.6B) to satisfy its demand for plastic using biogenic carbon in bioplastics. Clearly such a widespread management of biomass just for plastic, or even if land and biomass were shared with food, would not be ecologically feasible. The natural capital impacts would probably lead to system collapse (Bradley et al., 2026). The biocircularity framing provides valuable insights to this problem.

The third concept, the circular business ecosystem is essential. While design for circularity is necessary, if the technical system is not available to *actually* circulate materials and objects, then the circular system cannot function. There is an urgent need to help consumers by ensuring real meaning for the words used to describe products. A descriptor such as "organic" have a clear meaning that is regulated and well understood. A descriptor such as "sustainable" has no clear meaning and is not widely understood (Partidario et al., 2010). If consumers are to have understanding of, and

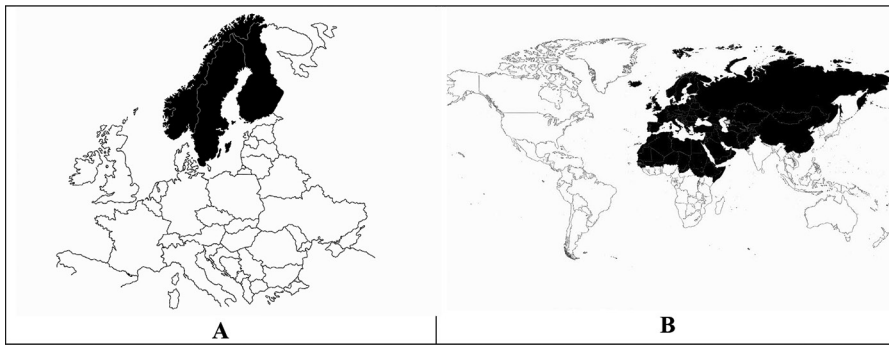

Figure 14.6 A. The area of the European Union that would need to be harvested of all biomass to satisfy demand for plastic for 1 year, were all plastics consumed to be made from biobased carbon. B. The area of the world the European Union would require to maintain supply of biomass to meet an ongoing demand for bioplastic assuming tree regrowth over 60 years. Source: drawn by ChatGPT with instructions from the author.

belief in, circular bioeconomy products, efforts must be made to clearly define and measure attributes of such products that relate to the intensions of bioeconomy and circular economy. It follows, that if a product can be reliably assessed against the biocircularity framework (whether as a formal ecolabel or some other way), this will help consumers make product selection choices that are good for the environment. If funders and investors can prioritise the financial support of bicircular designed products, and consumers can identify such products, then good choices have more chance of becoming the norm, and the simple framing will then emphasise and drive best practice across the plethora of product categories serving the European single market.

14.4 Conclusion

In conclusions, a final consideration is the implications of the biocircularity framework for the indicators used to measure progress towards the UN Sustainable Development Goals (SDG). This is important because the SDGs are globally recognised and accepted, so provide a route to impact and consumer acceptance. The most obvious examples are summarised in Table 14.1 (others are detailed in Holden et al., 2022). The framework has significant potential to drive reduced material footprint, reduced consumption (both related to decoupling), reduced food loss, greater recycling rates, framing education, reduced GHG emissions, and better management of ecosystems

Table 14.1 Summary of the implications of biocircularity for relevant SDG indicators.

Indicator	Indicator descriptor	Implication of biocircularity
8.4.1.	Material footprint, material footprint per capita, and material footprint per GDP	Circularity reduced material footprint. Consumers make better choices.
8.4.2.	Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP	Raw material consumption reduced due to decoupling. Consumers make better choices.
12.2.1	Material footprint, material footprint per capita, and material footprint per GDP	
12.2.2	Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP	
12.3.1	(a) Food loss index and (b) food waste index	Sustainably produced food waste circulated into products
12.5.1	National recycling rate, tons of material recycled	Circular business ecosystem drives recycling
12.8.1	Extent to which (i) global citizenship education and (ii) education for sustainable development are mainstreamed in (a) national education policies; (b) curricula; (c) teacher education; and (d) student assessment	Provides a framework and basis for strong sustainability education
13.2.2	Total greenhouse gas emissions per year	Impact reduced due to decoupling and biogenic carbon
15.1.2	Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type	Renewability criterion drives attention towards natural capital
15.4.1	Coverage by protected areas of important sites for mountain biodiversity	
15.4.2	(a) Mountain Green Cover Index and (b) proportion of degraded mountain land	
15.6.1	Number of countries that have adopted legislative, administrative and policy frameworks to ensure fair and equitable sharing of benefits	Quantifiable means of assessing policy and legislation

and natural resources. Most importantly, the biocircularity framework is founded on strong sustainability thinking (Ang et al., 2012), rather than the weak sustainability, techno-solutionism that predominates global responses to water, climate, and biodiversity crises. The framework is a way to start thinking about how to offer consumers products and businesses systems that actually make a difference.

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