Sustainability, circular economy and bioeconomy: A conceptual review and integration into the notion of sustainable circular bioeconomy

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Abstract

National legislation and international regulations are pushing societies to become more sustainable while meeting socio-economic demands. People are becoming more aware of their environmental impact and want more sustainable products and processes. However, the terminology around sustainability, circular economy, and bioeconomy can be unclear, and there is confusion about their boundaries and interpretation. This article contributes to the ongoing discourse within the scientific community by providing a clear and widely accepted definition of a sustainable circular bioeconomy, as well as insights and policy recommendations to facilitate its development into practice. The sustainable circular bioeconomy is a combination of circular economy and bioeconomy concepts that can contribute to achieving sustainability. The adoption of this concept can significantly contribute to the achievement of sustainable development goals related to responsible consumption and production, industry, innovation and infrastructure, poverty reduction, social equity, and environmental protection.

Keywords: *Sustainability, Circular economy, Bioeconomy, Circular bioeconomy, Sustainable development.*

1. Introduction

The terms sustainability, circular economy, and bioeconomy have gained momentum in recent years, moving from being restricted to academia to frequently appearing in the media, business action plans, and political strategies (European Commission, 2022). With the model of a society in transition, it is increasingly common to find citizens questioning whether current production systems are sustainable, and many

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of these citizens, generally uninitiated in these issues, are beginning to become familiar with these terms (Venkatesh, 2022). This change in consumer profile is primarily driven by concerns about climate change, global resource scarcity, and economic globalisation (Villarán *et al.*, 2018; Zabaniotou, 2018).

The transition towards more sustainable models requires more research and technology transfer, but this is hampered if the terminology is unclear and the actors involved are not aware of the differences between the concepts. The understanding and interpretation of these concepts varies depending on the actors involved (Näyhä, 2019). Within academia itself, the debate on the meaning of sustainability is still open, which hinders its use as a relevant global objective (Whyte and Lamberton, 2020). Similar issues with unclear and debated definitions of the circular economy (Corvellec *et al.*, 2021) and bioeconomy (Tan and Lamers, 2021) also hinder a more widespread application of the approaches underlying these concepts.

Furthermore, the boundaries between some of the concepts, such as sustainability and the circular economy, remain unclear (Geissdoerfer *et al.*, 2017). Although they have similarities and overlap in some aspects, they do not have the same meaning and are often confused. If we add the bioeconomy variable to the equation, the boundaries become even more blurred, making it necessary to review the origin and evolution of each term to understand its scope and use. In addition, new concepts, such as the circular bioeconomy, continue to emerge regularly, complicating the understanding of the meaning of the concepts and their applicability.

In this context, this article reviews the use of the concepts of sustainability, circular economy, and bioeconomy in the literature and sheds light on their boundaries. The aim is to answer the following research questions:

RQ1: How have the definitions of sustainability, circular economy, and bioeconomy evolved over time?

RQ2: What are the differences and overlaps between these concepts?

RQ3: How can these concepts, or their combinations, support the development of more sustainable systems?

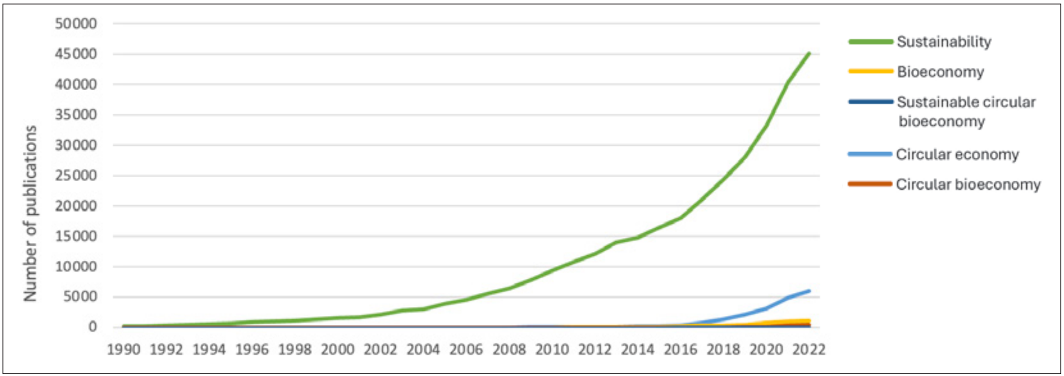
To answer these questions, a comprehensive analysis of each term is provided, highlighting their differences and commonalities. The aim of this study is to provide a theoretical basis for considering the postulates of the circular economy and the bioeconomy as tools for increasing the profitability of companies while minimising environmental impacts, and thus making systems more sustainable. The role that the novel concept of sustainable circular bioeconomy can play in this transition towards more sustainable systems is also discussed.

2. Methodology

The process of selecting references for this literature review was systematic and followed specific criteria. A more detailed breakdown of each step can be found below:

- Literature search: The first step was to conduct a literature search in the Scopus database. The search terms used were "sustainability", "circular economy" and "bioeconomy". The use of the terms "circular bioeconomy", that integrates the circular economy and bioeconomy, and "sustainable circular bioeconomy", that integrates sustainability, circular economy, and bioeconomy, was also explored. The aim was to find academic works in English language that used these terms in their title, abstract, or keywords, thus ensuring that they were central to the research.
- Time frame: The search covered the period from 1970 (earliest available data) to 2022 (latest full year), to capture the evolution of these concepts over time.
- Form of terms: Only noun forms of the terms were searched for, not adjectives. This was done to focus on articles that delve into the meanings and implications of the concepts themselves (such as "sustainability") rather than those that simply describe a process or product as being "sustainable".
- Inclusion of other sources: The literature search focused on journal articles and conference papers, but also included other relevant sources such as national legislation, international standards, and economic strat-

Figure 1 - Number of publications including the terms sustainability, circular economy, bioeconomy, circular bioeconomy, and sustainable circular bioeconomy by year.



egies, providing a broader and more practical context for these concepts.
- Selection criteria: Not all sources that mention the search terms were included in the review. To be selected, a publication had to meet one or more of the following criteria: the concepts were defined, the concepts were compared, or different approaches to the concepts were shown. This ensured that the selected sources contributed to a deeper understanding of the concepts.

Based on this criterion, 98 publications were selected for a thorough study. The next section presents the results obtained from the literature review and discusses the evolution of the concepts of sustainability, circular economy, and bioeconomy.

3. Evolution of the concepts in the literature

Figure 1 shows the number of publications found in Scopus for each concept by year. Although the search was carried out from 1970 onwards, Figure 1 only presents results from 1990 onwards, as until then the number of publications with the term "sustainability" was negligible (0-100 per year), while the number of publications with the terms "circular economy", "bioeconomy", "circular bioeconomy" and "sustainable circular bioeconomy" was nil (except for one publication by Ikeda (1979), who mentioned "bioeconomy", but in a different context to the one dealt with in this article).

Figure 1 clearly shows that "sustainability" is by far the oldest concept found in the literature, followed by "circular economy", "bioeconomy", "circular bioeconomy" and finally "sustainable circular bioeconomy". There has always been a clear predominance of publications on sustainability, while the number of publications focussing on the circular economy and the bioeconomy only started to increase from 2017. There are a negligible number of publications that have addressed the concept of (sustainable) circular bioeconomy so far. Moreover, only very few publications have addressed all or some of these concepts together. In addition, in most of the papers analysed, the concepts were introduced through the presentation of a case study, and only in a small number of them was the relationship between the concepts comprehensively analysed.

The next subsections analyse and discuss the importance, origin and evolution of the definitions, principles and critiques of the concepts of sustainability, circular economy and bioeconomy. Their boundaries, differences, and commonalities are highlighted. Table 1 summarises the elements of analysis for the three concepts.

3.1. *Sustainability*

The concept of sustainability dates back to the forestry treaties of the first half of the 18th century (Geissdoerfer *et al.*, 2017). In particular, it is based on the principle that the amount of timber harvested should never exceed the volume

Table 1 - Summary of the elements of analysis for sustainability, circular economy, and bioeconomy.

	Sustainability	*Circular economy*	*Bioeconomy*
The most common definition	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (sustainable development)	A system where materials never become waste and nature is regenerated	Production of renewable biological resources and their conversion into food, bio-based products, and bioenergy
Origin of the concept	18th century	Second half of the 20th century	Early 20th century
Principles	Three sustainability pillars/dimensions/domains: environmental, economic, and social	Eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature	Increase the applications of biotechnology, prioritise the use of bioresources, and consider ecological criteria
*Examples of usage in supranational agendas or standard*s	European Green Deal, 2030 Agenda for Sustainable Development	Circular Economy Action Plan (European Commission)	EU bioeconomy strategy
*Criticism and limitation*s	Lack of clearly established time dimension, lack of concrete objectives, and lack of specificity	Could generate outcomes such as those of the linear economy, high-energy consumption of recycling, and technical unfeasibility in certain situations	Use of bio-based resources does not guarantee a more sustainable system

planted. This principle of sustainability unites an economic criterion (i.e., maximum timber production securing the continuing existence of an individual business enterprise or livelihoods) and an ecological one (i.e., preserving a particular ecosystem). Subsequently, the concept of sustainability emerged from the field of ecology, referring to the respect for nature's ability to regenerate itself, giving rise to the modern conception of "sustainable is that which is capable of maintaining itself at a certain speed or level". In the late 18th century and the 19th century, the works of David Ricardo and Thomas Malthus, as well as those of the philosopher John Stuart Mill, are often considered the first systematic studies of the ecological limits on growth in a finite world and are credited with being an early source of critical sustainability. Malthus' *An Essay on the Principle of Population*, published in 1798, has been a very influential study on the relationship between population growth and resource scarcity (Malthus, 1798).

In the 20th century, the United States (US) National Environmental Policy Act of 1969 defined the US commitment to sustainability as the aim "to create and maintain conditions under which man and nature can exist in productive harmony, and fulfil the social, economic and other requirements of present and future generations" (United States Congress, 1969). This policy has been the basis for the national environmental policies of many other countries and has inspired the definition of sustainability most commonly used today.

However, it was not until the 1972 United Nations Conference on the Human Environment, also known as the Stockholm Conference, that the environment began to occupy the global political agenda. This conference led to the creation of the United Nations Environment Programme (UNEP) to protect ecosystems, tackle climate change, and promote green economic development. In the same year, the key report "The Limits to Growth", commissioned by the Club of Rome, was published (Meadows *et al.*, 1972). This report examined the results obtained by a computer simulation of the exponential population and economic growth in the context of a finite resource supply.

More aspects related to the concept of sustainability were studied in the following years. In 1983, the World Commission on Environment and Development was established to pursue sustainable development. This commission was chaired by the then Prime Minister of Norway, Gro Harlem-Brundtland, hence its common name “the Brundtland Commission”. The main outcome of this commission is the document “Our Common Future” published in 1987. This document, known as the Brundtland Report, defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). This was the first time that the concept of sustainability was associated with development. Indeed, both concepts share common synergies but show important differences. UNESCO (2012) defined them as “sustainability is often thought of as a long-term goal (i.e. a more sustainable world), while sustainable development refers to the many processes and pathways to achieve it”. Development objectives evolved from purely economic objectives to include social objectives (intragenerational equity) and environmental objectives (intergenerational equity). As a result, from the late 1980s and early 1990s onwards, development models have increasingly sought to move towards sustainability (environmental, economic and social).

The inclusion of these three sustainability pillars was further developed in the 1980s and 1990s. Stahel and Reday (1981) included measures clearly rooted in the three-fold dimension of the sustainability concept in their report on the Potential for Substituting the Manpower for Energy, commissioned by the European Commission. They introduced a purely circular production model, a loop economy based on measures such as waste prevention, regional job creation, and efficient use of natural resources, among others. This idea was further developed in the 1990s, when the idea of the triple bottom line was introduced to reflect the importance of three components (Ps) in any business decision: people, profit and planet (Elkington, 2013). Now, the three dimensions, i.e., social, economic, and environmental, are widely accepted and constitute the three domains of sustainability (Depetris-Chauvin *et al.*, 2023; Kirchherr *et al.*, 2017; Millar *et al.*, 2019; Näyhä, 2019; Zabaniotou, 2018). However, the importance of each dimension, particularly the environmental and economic dimensions, has been highly debated. This has caused the categorisation of sustainability into two types: weak and strong. Weak sustainability focuses on the economic domain and states that the aggregation of human capital and natural resources must be maintained intact over time. On the other hand, strong sustainability gives more importance to the environment and aims to keep only natural capital constant over time (Hediger, 1999). Finally, recent new trends related to sustainability include the concept of planetary boundaries, which aims to define the environmental limits within which humanity can operate safely (Steffen *et al.*, 2015). However, this only looks at the environmental domain of sustainability.

The concept of sustainability is currently part of the political agendas of most countries and the strategies of most large organisations. For instance, the European Green Deal aims to contribute to environmental sustainability by transforming the EU economy to eliminate net greenhouse gas emissions by 2050 and decoupling economic growth from resource use (European Commission, 2019). Similarly, the US proposed a Green New Deal in 2019 to address climate change as well as social challenges such as economic inequality and access to clean water (Friedman, 2019). Although the legislation was rejected by the Senate, it was reintroduced in 2021. The US has already implemented a number of other environmental sustainability policies, such as the Clean Air Act, the Clean Water Act, and the Endangered Species Act. At the global level, the United Nations General Assembly established the 2030 Agenda for Sustainable Development, which defined 17 Sustainable Development Goals (SDGs) and 169 targets to be achieved by 2030. This Agenda was adopted by Heads of State and Government in 2015 (United Nations, 2015) and is shaping sustainability policies designed in all countries of the world. Despite being instrumentalised, the concept of sustainability has become as entrenched as the principles of democracy, justice and freedom (Geissdoerfer *et al.*, 2017; O’Riordan, 1988).

Despite its widespread everyday use, there are criticisms of the concept of sustainability. One of its main weaknesses is that it only indicates that future generations cannot be deprived of satisfying their own demands, without a clearly established time dimension (Ulhoi and Madsen, 1999). Moreover, its concrete objectives have not been specified either, as these objectives are normative determinations that cannot be derived solely from scientific-descriptive models (Valentin, 2018). Consequently, empirical and quantitative data on their implementation are not abundant (Ritzén and Sandström, 2017). This lack of specificity is the main argument put forward by detractors of the concept of sustainability, who consider it only a buzzword that does not materialise in actions, policies or laws.

Kirchherr *et al.* (2017) also argued that although the concept of sustainability dates back to the 18th century, and despite the popularity of Brundtland's definition of sustainable development, it is still considered too broad a concept, making it difficult to put into practise. Other authors go further and question what should be sustained, for how long, and for whose benefit (Giampietro and Mayumi, 2009). Sustainability claims have also been used by companies for "greenwashing", in order to divert attention to minor issues or to create a "green talk" (Siano *et al.*, 2017).

Some authors, such as Ruggerio (2021), argued that sustainability is not a state that systems can achieve, i.e., systems cannot be labelled as "sustainable", but only as "more sustainable" or "less sustainable" than alternative systems. This means that sustainability is not an end goal but a path towards more sustainable systems. Other authors and institutions, such as UNESCO, distinguish "sustainability" from "sustainable development", and set the former as a long-term goal, while using the latter to refer to pathways to achieve it (UNESCO, 2012). According to this commonly followed view, sustainability can be seen as an idealistic theoretical goal, but the concept itself does not define what concrete practical path should be followed to achieve it.

In conclusion, sustainability is a holistic concept with a clear generic objective: not to overexploit natural resources beyond their recovery capacity, having a positive impact on the three pillars on which it is based (economic, social and environmental). However, if this objective is not translated into time-bound actions and responsibilities, it runs the risk of becoming utopian.

3.2. *Circular economy*

The concept of circular economy was first used in the second half of the 20th century. One of its main promoters was the English economist Kenneth E. Boulding, author of the essay "The economics of the coming spaceship Earth" (Boulding, 1966), in which he drew a parallel between a human being on Earth and an astronaut in his spaceship. According to Boulding, economists in general do not consider the Earth to be a closed system, but on the contrary, matter, energy, and information seem to come from elsewhere, as if natural resources were inexhaustible. Similarly, waste also seems to flow out of the system to some other place of infinite absorptive capacity. Although many economists used to think in this way, as early as in the early 19th century, leading economists such as David Ricardo, Thomas Malthus, and Stuart Mill had already warned about the limits of the planet. In this context, one of the basic ideas of the circular economy is to consider the waste of one process as an input into other production processes, contrary to the prevailing linear economy, also known as the "take-make-waste" economy (Suttie *et al*., 2017). In fact, one of the principles of the "cradle-to-cradle" philosophy, on which the circular economy is based, is that "waste equals food", which encourages designing processes in such a way that their waste can be "food" for other systems (Ellen MacArthur Foundation, 2013).

The concept of the circular economy is based on the idea that natural resources are not infinitely available to humans, nor is nature's capacity to absorb the waste generated by human activity infinite (Boulding, 1966). This is similar to the concept of sustainability. The main novelty introduced by the circular economy is, as its name suggests, the circularity of the production model as opposed to the prevailing linearity. This means that production must be seen as a cycle that cannot be closed without returning to the starting point. Hence, the term "closed-loop economy", is a concept similar to that of the circular economy (Ellen MacArthur Foundation, 2013; (Ellen MacArthur Foundation, 2013; Saidani *et al.*, 2022).

There are many definitions of circular economy, but to date there is no consensus on which one should be accepted by the scientific community (Korhonen *et al.*, 2018b; Yuan and Moriguichi, 2006). Kirchherr *et al.* (2017) and Millar *et al.* (2019) noted the scarcity of studies investigating or contrasting the different definitions of circular economy. This makes it difficult to disseminate and use the concept (Kalmykova *et al.*, 2018). In addition, the foundations of the circular economy are based on many other concepts, such as steady-state economics, industrial ecology, cradle-to-cradle philosophy and others (Kalmykova *et al.*, 2018).

Bastein *et al.* (2013) defined the circular economy as an economic and industrial system based on the reuse of products and raw materials and the resilience of natural resources, in which value destruction is minimised and value creation is maximised throughout the system. Yuan and Moriguichi (2006) proposed a simpler definition: a system in which the flow is circular and raw materials and energy are used in multiple phases. To achieve this goal, the life cycle of products needs to be redesigned (D'Amato *et al.*, 2017).

According to the Ellen MacArthur Foundation (2015), the circular economy is based on three principles: 1) preserving and enhancing natural capital by controlling finite stocks and balancing renewable resource flows; 2) optimising resource use by rotating products, components, and materials with maximum utility at all times, in both technical and biological cycles; and 3) fostering system efficiency by revealing and eliminating negative externalities. These principles perfectly coincide with the concept of sustainability.

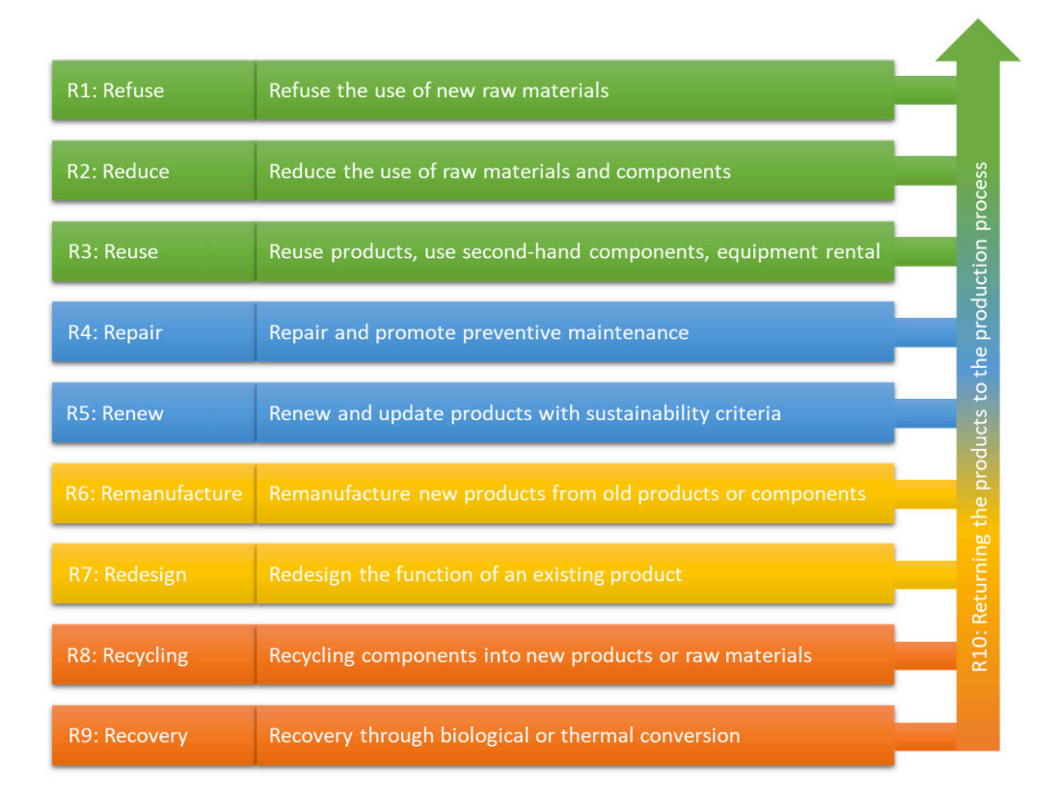
The circular economy not only increases resource efficiency by minimising waste and resource use but also considers the economic, environmental and social domains, as does the concept of sustainability (Ghisellini *et al.*, 2016; D'Amato *et al.*, 2017; Näyhä, 2019). In 2015, the European Commission itself adopted an action plan to help accelerate Europe's transition towards a circular economy that explicitly mentions the use of resources in a sustainable way, with actions that are beneficial for both the economy and the environment (European Commission, 2015).

The circular economy is also often related to the 3Rs principle, which promotes reduce, reuse, and recycle, in this order (Ghisellini *et al.*, 2016; Yuan and Moriguichi, 2006). Ritzén and Sandström (2017) and Kalmykova *et al.* (2018), among others, added a fourth R, recover, to refer to options such as energy recovery, which should always be the last preferred option. Van Buren *et al.* (2016) and Potting *et al.* (2017) included economic, social, and environmental value creation as primary objectives, embodied in a framework of the following 9Rs: 1) refuse the use of new raw materials; 2) reduce the use of raw materials; 3) reuse products; 4) repair and maintain; 5) renew products; 6) remanufacture; 7) redesign; 8) recycle; and 9) recover energy. For Kirchherr *et al.* (2017), the circular economy is also based on this framework, but with an emphasis on prioritising prevention over the other options. We suggest adding the tenth R, which would be "return" (Figure 2), to emphasise that all physical products generated in the system, including by-products and waste, should remain in the same or a different production system. R10 completely closes the circular system.

The circular economy continues to gain momentum and is even seen as a replacement for the linear economy as a production system. This is reflected in the fact that some of the world's most developed nations include it in their policies, such as China, the European Union, and the United States (Circular CoLab, 2018; European Environment Agency, 2018a; World Bank Group, 2009). The private sector has also begun to explore the opportunities offered by the circular economy (Ellen MacArthur Foundation, 2013).

Two factors have driven the development of the circular economy: 1) China's adoption of this concept as a development strategy in 2002 and its implementation in its national policy in 2006 (Yuan and Moriguichi, 2006) and 2) the launch of the Ellen MacArthur Foundation in 2010 by yachtswoman and elite athlete Ellen McArthur in partnership with five major multinationals, with the aim of "accelerating the transition to a circular economy" (Suttie *et al.*, 2017). In fact, one of the most widespread definitions of the circular economy is that of the aforementioned foundation, which defines it as "a system where materials never become waste and nature is regenerated" (Ellen MacArthur Foundation, 2023). The circular econ-

Figure 2 - The 10R principle. Own elaboration partly based on van Buren et al. (2016) and Potting et al. (2017).



omy is "one that is restorative and/or regenerative in intention and design" (Ellen MacArthur Foundation, 2013) and has as principles to eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature (Ellen MacArthur Foundation, 2023).

There are also negative views on the circular economy in academia. Some authors think that the circular economy could generate outcomes similar to those of the linear economy (Millar *et al.*, 2019) if changes do not come from the core of the system, i.e., the business model (Bocken *et al.*, 2014). Others warn of the high-energy consumption of recycling, which is sometimes higher than that of manufacturing/extraction of new materials (Allwood, 2014), which could make the energy efficiency of the recycling process lower than that of the manufacture/extraction of new materials. Giampietro (2019) argued that the circular economy is not thermodynamically feasible, as entropy increases in each closed loop, leading to losses in quantity (materials, by-products, etc.) and quality (mixing, degradation). This is in line with the work of Allwood (2014), who argued that the circular economy would only be technically feasible if global demand for products were stabilised, and of Korhonen *et al.* (2018a) who considered the possibility of circularising the economy to be unfeasible. Furthermore, Korhonen *et al.* (2018a) argued that the definition of circular economy should also refer to a reduction in production to levels that are acceptable to nature.

Few articles have analysed both the circular economy and sustainability at a theoretical level. Among the few exceptions is the work of Geissdoerfer *et al.* (2017), who, based on an in-depth literature review, studied the differences and similarities between the two concepts, as well as the types of relationships that exist between them. In terms of similarities, they pointed out the intergenerational nature of the commitments and the need for greater intervention by institutions as a vehicle for development. Other common aspects are the global approach, the interdisciplinary nature of their object of study, and the necessary cooperation between different actors. Regarding the most notable differences, it is worth highlighting the open and unspecific objectives of sustainability, with a diffuse temporal dimension, as opposed to the objective of a more efficient use of resources promoted by the circular economy. Finally, although sustainability gives importance to its three domains, weak sustainability gives more importance to the economic domain, whereas strong sustainability focuses more on the environmental domain. In the circular economy, the economic system predominates, with environmental and social gains being little more than collateral (Murray *et al*., 2017). There is a broad consensus in the literature on the similarities and differences indicated, except the last point.

In conclusion, the circular economy, in terms of objectives and fundamental principles, fits very well with the concept of sustainability, albeit with some nuances. Indeed, the circular economy is often seen as an indispensable element for achieving sustainable development (Läpple, 2007; Näyhä, 2019; Yuan and Moriguichi, 2006) and could therefore be the instrument to concretise sustainability in a legal framework and align the actors involved.

3.3. *Bioeconomy*

The term "bioeconomy" was first coined in the 1920s by the Russian biologist Baranoff to describe the economics of the fisheries sector. It then became generalised in the 1950s, referring to the need to use renewable resources, and was consolidated in the 1970s and 1980s as an ecological perspective applied to economics (Giampietro, 2019), with the Romanian mathematician and economist Georgescu-Roegen at the forefront. In the last decade, the bioeconomy has gained great popularity and has been studied and disseminated by international organisations such as the Organisation for Economic Co-operation and Development (OECD, 2009). The bioeconomy has been placed at the centre of the political strategies of major powers such as the United States and the European Union (Guo and Song, 2019), in coexistence with circular economy strategies.

For Vivien *et al.* (2019) and Befort (2020), the original concept of bioeconomy has evolved into two new meanings that are very different from the original. The first new meaning emerged between the 1990s and 2000s with the biotechnology revolution and places biotechnology at the centre of the bioeconomy. It is part of the so-called knowledge economy or economy based on scientific knowledge and research. The second new meaning, currently dominant in the European Union, is the so-called biomass bioeconomy, which encompasses sectors as diverse as energy, agriculture, fisheries, forestry, chemistry, as well as biotechnology itself, as suppliers of the raw materials transformed in the so-called biorefineries. This new term refers to industries that process different types of biomass (wood, agricultural products, waste and algae) with the aim of replacing fossil fuels.

The multiple definitions of bioeconomy found in the literature agree with the two new meanings mentioned above. Thus, De Besi and McCormick (2015), McCormick and Kautto (2013), and Suttie *et al*. (2017) defined it as an economy based on the sustainable production and conversion of biomass into bio-based materials or energy. Very similar is the definition of the European Commission (2018), according to which the bioeconomy is the production of renewable biological resources and their conversion into food, bio-based products, and bioenergy, affecting sectors as diverse as agriculture, forestry, fisheries, the food industry, the paper industry, as well as some chemical, biotechnology, and energy industries. The perception of biomass as the basis of the bioeconomy is shared by other authors (Aguilar *et al*., 2018; Lainez *et al*., 2018; Lewandowski, 2015; Näyhä, 2019; Villarán *et al*., 2018; Wohlfahrt *et al*., 2019). The exact definition of the bioeconomy varies from region to region, from organisation to organisation and even between different stakeholders (McCormick and Kautto, 2013; Näyhä, 2019).

On the other hand, for organisations such as the OECD, the bioeconomy is the result of the application of biotechnology to production, based on the development and use of biological materials, with potential benefits for the economy and the environment (OECD, 2009). Although this definition straddles the two new meanings outlined by Vivien *et al.* (2019), it gives biotechnology a leading role.

Bugge *et al.* (2016) also distinguished three conceptions of the bioeconomy, albeit from a different perspective. The first conception is framed within a scientific vision, which emphasises the need to deepen research to increase the applications of biotechnology and, therefore, the commercialisation of its results. The second, more along the lines of De Besi and McCormick (2015), prioritises the use of so-called bio-resources and promotes research into new raw materials of biological origin and the establishment of new value chains. In contrast to the first conception, which prioritises further biotechnology transfer, the second focuses on the potential for adaptation and conversion of new bio-based materials to existing industrial processes. Finally, a third vision focuses on bioecology, i.e., the importance of taking ecological criteria into account in industrial processes, optimising energy and nutrient use, and promoting biodiversity while avoiding monocultures and soil degradation. Although this third vision does not fully correspond to the initial concept of bioeconomy promoted by Georgescu-Roegen, it is the closest and the only one that explicitly includes ecology.

Although there is some overlap between the bio-based and biotechnology-based streams, they are completely independent of the original ecological stream. This has led some authors (e.g. Giampietro, 2019; Plumecocq, 2014; Vivien *et al*., 2019) to call for a return to the concept put forward by Georgescu-Roegen and to argue that the transition of the current economic system must involve a change based on ecological principles. These three streams that make up the concept of the "bioeconomy" are described in more detail below, and their relationship to sustainability and the circular economy is discussed.

In terms of biomass use, the potential for new functions and properties of biological versus non-biological resources represents an open door for innovation, which should be implemented in the economic context (Aguilar *et al*., 2018). According to Suttie *et al.* (2017), the preferential use of bio-based materials over fossil-based materials could be considered a subcategory of the circular economy, as it would help achieve waste minimisation. There are many examples of this use of biomass to support the transition to a circular economy, e.g., the substitution of polypropylene by plant fibres such as jute or hemp in the manufacture of raffia and other growing materials (Hitschfeld and Rodríguez, 2015; Marín-Guirao *et al*., 2022). If the trellis elements were compostable, at the end of their useful life, they could be sent to a composting plant together with the plant waste (Sayadi-Gmada *et al*., 2019). In this way, they would cease to be waste and would be transformed into a new product, which could also be returned to the farm in the form of compost, thus closing the cycle (Castillo-Díaz *et al*., 2022).

As for the biotechnology stream of the bioeconomy, one of its objectives is to obtain high value-added products from biomass (Egea *et al*., 2018 and 2021), which can again be perfectly integrated into the objectives of the circular economy if the biomass used as raw material is a waste (Pinela *et al*., 2017). For example, biotechnology makes it possible to extract active compounds from plant waste, such as carotenoids, lycopene (Pinela *et al*., 2017; Villarán *et al*., 2018), organic acids, enzymes (Irfan *et al*., 2020), microorganisms, and proteins (Leceta *et al*., 2014). This means that countries with a high dependence on agriculture and the agri-food industry could find an alternative to their usually costly waste management, bringing an economic benefit that, for example for the Netherlands, is estimated at EUR 3.5 billion per year (Bastein *et al*., 2013). Another objective of biotechnology is the production of alternative materials that can satisfy specific applications without becoming waste that is difficult to manage, such as biodegradable or compostable plastics for agricultural mulch (Blanc *et al*., 2019).

As for the ecological stream of the bioeconomy, Georgescu-Roegen's conception is a priori compatible with the circular economy. On the one hand, a circular model is more easily integrated into biogeochemical cycles than the dominant linear model (Leipold and Petit-Boix, 2018). On the other hand, the circular economy is strongly rooted in industrial ecology (Mirabella *et al.*, 2014) and economic degrowth (Vivien *et al.*, 2019). In this sense, they share common ideas, such as waste minimisation, which can help optimise the use of energy and materials in the system (Bugge *et al.*, 2016). However, beyond the above, no other similarities have been found between the bioeconomy and the circular economy. On the contrary, the material and energy limits of recyclability are questioned. Indeed, the use of biomass and biotechnology has proven to be compatible with the circular economy. However, for proponents of a more orthodox idea of the bioeconomy, mainly ecological economists, the combination of biotechnology, use of biomass resources, and circular economy is not sufficient to harmonise natural cycles with the current production system.

From the above discussion, we can see the urgency of delving deeper into each of the three coexisting streams in the bioeconomy to unify them not only around the principles of the circular economy but also according to economic, social, and environmental criteria, i.e., from an eminently sustainable perspective. An approximation to the definitive definition of the bioeconomy could be as follows: the bioeconomy is an ecologically based production model based on two pillars: 1) the use of biological resources and 2) the use of biotechnology. The former represents the raw materials, while biotechnology is the instrument to implement it. However, to ensure the sustainability of the system, the central core must be ecology.

It should be noted that the use of bio-based resources in the production process does not guarantee a more sustainable system (Ramcilovic-Suominen and Pülzl, 2018; Tan and Lamers, 2021). For example, it is uncertain that biodegradable plastics can fully degrade under uncontrolled conditions, especially in oceans where temperatures are lower (Tulashie *et al.*, 2019). This creates a major marine pollution problem. On the other hand, when biodegradable materials decompose rapidly, they release greenhouse gases, increasing global warming more than non-biodegradable materials in the short term. Another example is the indiscriminate increase in bio-crops, which leads to deforestation and land-use change, which in turn leads to the loss of carbon sinks (Suttie *et al.*, 2017; Zabaniotou, 2018), threats to natural ecosystems (Aguilar, 2018; Bohlin *et al.*, 2011), increased pollution from agro-industry, impacts on biodiversity from unsustainable soil and water management practices (Kayatz *et al.*, 2019; Santos-Martín *et al.*, 2019), and competition between bioresource production and food production (Baumgarten and Kerckow, 2017; Bobe *et al.*, 2014; Martínez de Arano *et al.*, 2018).

A radical transformation towards biorefineries has several risks, not only for the reasons outlined above, but also because 1) the industry has been in existence for several centuries, so it is not feasible to replace it in such a short time (Mirabella *et al.*, 2014; Nielsen *et al.*, 2020), and 2) the replacement of the facilities would generate such a large amount of waste that it would be difficult to manage it in a sustainable way (Vinyes *et al.*, 2017). On the other hand, the powerful lobbies of the petrochemical industry could simply renew their feedstocks and continue to produce unsustainably (Vivien *et al.*, 2019).

From the above discussion, it can be concluded that the circular economy and the bioeconomy tend to be seen as complementary rather than antagonistic (Beltrán, 2018; D'Amato *et al.*, 2017; EEA, 2018). Their points of convergence include boosting local production and developing rural areas (Aguilar, 2018; Bugge *et al.*, 2016; Näyhä, 2019). The circular economy can boost local production by using the waste generated locally, similar to the bioeconomy, which should prioritise the use of local biological resources over biomass from distant locations. Promoting local production also supports the development of rural areas, where large amounts of biomass, for instance from agricultural activities, are generated. Furthermore, the use of biological resources at the local level, as well as appropriate technologies to valorise them instead of exporting them, creates added value and synergies in innovation and development (Bugge *et al.*, 2016), with implications for job creation and a lower carbon footprint due to the elimination of transport. This has led to the merging of the terms into one that integrates the fundamental principles of both: circular bioeconomy.

4. Towards a sustainable circular bioeconomy

The concept of sustainability, as mentioned above, is broad, holistic, and abstract; therefore, it needs a unanimous definition in order not to become a utopia, as well as tools to materialise it. These tools can be the circular economy and the bioeconomy. The principles of the circular economy and the bioeconomy are synergistic in terms of the goal of achieving socio-economic development by decoupling economic growth from resource depletion and environmental degradation (Lokesh *et al.*, 2018). Moreover, a fully functional bioeconomy is completely compatible with the achievement of a circular economy, both at the micro (local rural development) and macro (national) levels (D'Amato *et al.*, 2017; Tan and Lamers, 2021). Indeed, the bioeconomy, along with the circular economy, has the potential to contribute directly to the UN Sustainable Development Goals, which are today's main targets for sustainable development. However, a broader view should be taken, considering the circular bioeconomy as a type of interaction that belongs to a broader concept than the bioeconomy and the circular economy (Raimondo *et al.*, 2021).

There is little previous work on the implementation of a circular bioeconomy to achieve sustainable systems. At the policy level, examples range from the local level, such as the pilot project on circular bioeconomy for organic waste in Sangüesa (Spain) (Gobierno de Navarra, 2017), the regional level, such as the Andalusian Strategy for the Circular Bioeconomy (Junta de Andalucía, 2017), to the international level, with the European Commission leading the way (European Commission, 2022). The European Commission defines the circular bioeconomy as the production of energy, food, platform chemicals, and other bio-based materials and compounds from biomass in a sustainable and integrated/cascading manner (biorefinery) while generating zero waste. Although the circular bioeconomy is generally conceived as a sustainable alternative, it must be implemented through a legal framework based on environmental, economic, and social principles, so that the attractiveness of new business opportunities resulting from the combination of the circular economy and the bioeconomy remains sustainable.

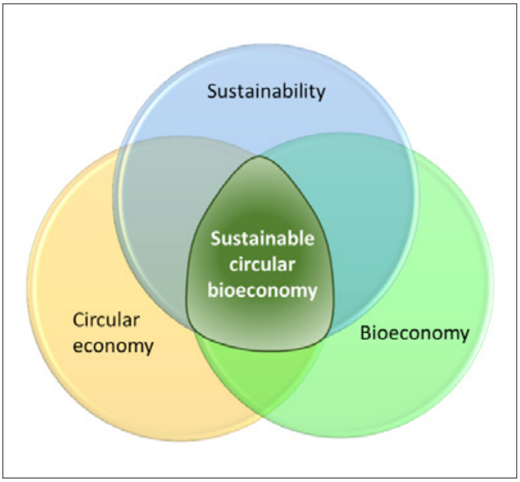
In fact, neither the bioeconomy nor the circular economy are inherently sustainable, although both concepts can be used as approaches to make a system more sustainable. Moreover, both the bioeconomy and the circular economy complement each other; therefore, the ideal production model would be one that brings together the strengths of both systems. Therefore, in our view, the ultimate strategy should be a sustainable circular bioeconomy, a combination of what should be done (the circular economy) and how it should be done (the bioeconomy) to achieve economic, social, and environmental benefits (sustainability).

In the literature review presented in Section 3, the term "sustainable circular bioeconomy" was found in 48 articles. However, these articles only claimed to use this approach in their work, without providing a precise definition or explanation of the approach. Only five articles provided a partial definition of the concept, focussing on different aspects, such as the use of natural resources (Krüger *et al.*, 2020), biomass utilisation (Sevigné-Itoiz *et al.*, 2021), bio-waste valorisation (Briassoulis *et al.*, 2021), and the use of by-products in biorefineries (Khan *et al.*, 2022). Zabochnicka (2022) integrated the three main concepts (i.e. sustainability, circular economy and bioeconomy) but only provided the following generic definition: "sustainable circular bioeconomy is an element of the circular economy that is connected to all processes, products and technologies that are "bio", and aims at sustainability".

On the basis of the discussion above and the literature review presented in Section 3, we propose the following definition of sustainable circular bioeconomy: "a deeply ecologically based production model that produces social, environmental, and economic benefits by integrating the principles of the circular economy and the bioeconomy". In this context, the three concepts (i.e. sustainability, circular economy and bioeconomy) can be represented with a Venn diagram, with clear overlaps as well as distinct areas for each concept (Figure 3). The ideal strategy corresponds to one that integrates all three concepts: the sustainable circular bioeconomy (darker central area in Figure 3). Therefore, a sustainable circular bioeconomy is an economic system that prioritises sustainable production and consumption practices, while integrating principles from the circular economy and the bioeconomy. In a sustainable circular bioeconomy, the production and consumption of goods and services are based on principles of environmental and social responsibility. This means that economic activity is designed to support the long-term health of the planet, while also benefiting society through job creation, poverty reduction, and improved access to resources and services. One of the implications of this model is that it requires a significant shift in the way we approach production and consumption. Instead of a linear take-make-dispose model, the sustainable circular bioeconomy emphasises the importance of circularity and waste reduction. This requires a shift towards closed-loop systems that minimise waste and maximise the reuse of resources. Another implication is that the sustainable circular bioeconomy can create new opportunities for innovation and economic growth. For example, it can foster the development of new technologies and business models that prioritise sustainable production and consumption practices. It can also create new employment opportunities in areas such as recycling and resource management. Finally, the sustainable circular bioeconomy has important implications for environmental and social sustainability. Prioritising the long-term health of the planet and supporting equitable access to resources and services has the potential to reduce poverty, promote social justice and protect natural resources and ecosystems.

It should be emphasised that consumers are not only a key factor in setting product prices but also encourage the production of certain products to the detriment of others. The criteria traditionally considered by consumers, such as aesthetics, performance, price, or brand, have started to include the sustainability of the production process and of the product itself. Thus, the shift towards more sustainable systems must start from the citizens, not only because of their power as consumers, but also because of their growing awareness of their own waste generation and its associated impacts on the environment. Due to growing public awareness, citizens are expected to embrace the principles of a sustainable circular bioeconomy.

Figure 3 - Relationships among the concepts of sustainability, circular economy, bioeconomy, and sustainable circular bioeconomy.



The proposed definition and concept of a sustainable circular bioeconomy can contribute to the achievement of sustainable development and multiple SDGs in several ways: 1) the sustainable circular bioeconomy prioritises sustainable production and consumption practices, which is in line with SDG 12 'Responsible consumption and production'; by adopting circular economy principles such as waste reduction and resource efficiency, it can contribute to reducing the environmental impact of production and consumption; 2) the sustainable circular bioeconomy can create new opportunities for innovation and economic growth, which is in line with SDG 9 'Industry, innovation and infrastructure'; it can foster the development of new technologies and business models that prioritise sustainable production and consumption practices, which can contribute to job creation and economic growth; 3) the sustainable circular bioeconomy can help reduce poverty and promote social justice, which is in line with SDG 1 'No poverty' and SDG 10 'Reduced inequalities'; by creating new employment opportunities in areas such as recycling and resource management, it can generate income and support livelihoods, especially for disadvantaged communities; and 4) by prioritising the long-term health of the planet and supporting equitable access to resources and services, the sustainable circular bioeconomy can contribute to the protection of natural resources and ecosystems, which is in line with SDG 13 'Climate action', SDG 14 'Life below water' and SDG 15 'Life on land'.

Building on the concept of a sustainable circular bioeconomy and the preceding discussion, a number of public policies can be developed to put the concept into practice, including the following:

- Establishing regulatory frameworks: Policies should be developed to establish legal frameworks in line with environmental, economic, and social principles to ensure the sustainability of the circular bioeconomy. This will help to regulate the business opportunities arising from the combination of the circular economy and the bioeconomy.
- Encourage the use of biomass: Policies should be developed to promote the use of biomass in a sustainable manner with the aim of achieving zero waste. This can be achieved by promoting the use of by-products in biorefineries, the valorisation of bio-waste, and the use of natural resources.
- Develop pilot projects: Pilot projects on circular bioeconomy should be promoted at the local level. These pilot projects can serve as a blueprint for other regions to follow, leading to the development of sustainable circular bioeconomies at the regional level.
- Create new market opportunities: Marketing strategies should focus on creating new market opportunities based on quality attributes to meet consumer demand for more sustainable products.
- Promote the uptake of new technologies: The adoption of new technologies can enhance the sustainability of systems and products. An example of this is the use of digital technologies to collect and analyse large volumes of data in real time, which allows the optimisation of production processes as well as the use phase of the products.
- Educate citizens: Actions should be taken to communicate and educate citizens about the principles of a sustainable circular bioeconomy. This will enable citizens to make informed choices about their consumption patterns and waste generation. In addition, consumer preference for sustainable products can encourage businesses to adopt sustainable production models.
- Work together at international level: Collaboration at the international level can help promote the sustainable circular bioeconomy. The European Commission has taken the lead in this regard, and more such collaborations can be established to share best practices and ideas.

5. Conclusions

This article has revised the definitions and use of the concepts of sustainability, circular economy, bioeconomy, and circular bioeconomy. The concept of sustainability has been widely accepted for a long time and is based on the principle of not overusing natural resources beyond their capacity for recovery. It has a triple dimension of social, economic, and environmental considerations, but its objectives are not clearly defined and the responsible actors are yet to be identified. The circular economy aims to optimise the use of resources and minimise waste generation by integrating them into a circular production model. It prioritises the economic dimension, but the importance of the social and environmental dimensions remains a subject of debate. The bioeconomy is divided into three streams: the original ecological concept, the biomass-based bioeconomy, and the biotechnology-based bioeconomy. The core of the bioeconomy is ecology, and biotechnology is the instrument for its application.

The integration of these concepts results in the concept of a sustainable circular bioeconomy. The sustainable circular bioeconomy uses waste as input for another or the same process, prioritises the use of biological materials over those of fossil origin, and uses biotechnology to generate social, environmental, and economic benefits. Implementing a sustainable circular bioeconomy requires efforts from multiple actors. The scientific community must reach a consensus on its definition, objectives, and levels of action. The aim of our study is to contribute to the ongoing discourse within the scientific community on the need to establish a clear and widely accepted definition of sustainable circular bioeconomy. Given the growing global interest in this emerging field, it is imperative that a consensus is reached on the fundamental concepts and principles that underpin this paradigm shift towards a more sustainable, resource-efficient, and regenerative economic model. Our work aims to provide insights and recommendations to facilitate the development of a common understanding of the sustainable circular bioeconomy, enabling stakeholders to work together more effectively to achieve its goals.

In addition to efforts at the theoretical level, public institutions should provide support and credibility to the concept and implement it in practice through regulations at the international and national levels. Governments must rely on scientific knowledge to design and implement strategies, while industry must apply this concept to become more competitive, enter new markets, and increase profitability. The role of citizens is also crucial in spreading environmental values and cultivating a culture of sustainability. They must understand the impact of their daily activities on the environment, particularly from the waste they generate. In conclusion, the sustainable circular bioeconomy is key to increasing sustainability in our societies, and all actors must play their part in achieving it. Adopting the principles of a sustainable circular bioeconomy can significantly contribute to the achievement of sustainable development and several SDGs, particularly those related to responsible consumption and production, industry, innovation and infrastructure, poverty reduction, social equity, and environmental protection.

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