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El Concepto de Bioeconomía Circular: Origen, Evolución y Perspectivas para México

The Concept of Circular Bioeconomy: Origin, Evolution and Perspectives for México

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Abstract

This work's main objective is to analyze the fundamental principles and concepts of the circular bioeconomy, as well as to explore its development possibilities in the Mexican context. For this purpose, a methodology of conceptual and evolutionary analysis is used, based on a critical review of the historical evolution of approaches such as sustainability, green economy, circular economy and bioeconomy. This analysis allows contextualizing the circular bioeconomy as a concept under construction, resulting from the convergence of previous theoretical frameworks oriented towards a sustainable transition. Some of the relevant findings highlight that, despite its potential to foster a regenerative and low-carbon economy, the circular bioeconomy faces significant challenges: conceptual ambiguity, lack of specific and standardized indicators, and weaknesses in institutional frameworks. It also points to the need for multi-sectoral approaches, as well as a cultural transformation to encourage its adoption at various social and productive levels. A limitation of the study is the scarcity of previous research in the Latin American context, especially in Mexico, which evidences a relevant knowledge gap. However, this also highlights the originality of the work, as it is one of the first systematic academic approaches to the subject in the country. In conclusion, it is argued that the circular bioeconomy offers a strategic way to integrate natural capital into productive systems, proposing a new economic paradigm that is more sustainable, inclusive and adapted to the socio-environmental challenges of the 21st century.

Keywords: Circular Bioeconomy, Environment, Regenerative Economy, Sustainability, Circular Economy.
JEL Classification: Q01, Q56, O13, Q57, R11.

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Resumen

El objetivo principal de este trabajo es analizar los principios y conceptos fundamentales de la bioeconomía circular, así como explorar sus posibilidades de desarrollo en el contexto mexicano. Para ello, se emplea una metodología de análisis conceptual y evolutivo, basada en la revisión crítica de la evolución histórica de enfoques como la sustentabilidad, la economía verde, la economía circular y la bioeconomía. Este análisis permite contextualizar la bioeconomía circular como un concepto en construcción, resultado de la convergencia de marcos teóricos previos orientados a una transición sostenible. Entre los principales hallazgos destaca que, a pesar de su potencial para fomentar una economía regenerativa y baja en carbono, la bioeconomía circular enfrenta desafíos importantes: ambigüedad conceptual, ausencia de indicadores específicos y estandarizados, y debilidad en los marcos institucionales. Además, se señala la necesidad de enfoques multisectoriales, así como de una transformación cultural que fomente su adopción en diversos niveles sociales y productivos. Una de las limitaciones del estudio es la escasez de investigaciones previas en el contexto latinoamericano, especialmente en México, lo cual evidencia una brecha de conocimiento relevante. No obstante, esto también resalta la originalidad del trabajo, al constituirse como una de las primeras aproximaciones académicas sistemáticas al tema en el país. En conclusión, se argumenta que la bioeconomía circular ofrece una vía estratégica para integrar el capital natural en los sistemas productivos, proponiendo un nuevo paradigma económico más sostenible, inclusivo y adaptado a los desafíos socioambientales del siglo XXI.

Palabras clave: economía circular, recursos naturales, regeneración, sustentabilidad, bioeconomia circular.
Clasificación JEL: Q01, Q56, O13, Q57, R11.

1. Introduction

In a global context where the climate crisis, the degradation of natural resources, and the urgent need for sustainable development models are major issues, the circular bioeconomy is emerging as an alternative that seeks to integrate sustainability with economic and social development. This model promotes the efficient and regenerative use of renewable biological resources through production systems that combine technological innovation, biomass use, circular economy and environmental preservation. The European Union (EU) and the United States (US) have adopted specific strategies to develop this alternative model and thus accelerate the transition to a low-carbon economy that guarantees a high quality of life (IPBES, 2019; Frisvold, *et al*., 2021; Richter *et al*., 2025).

For this reason, the circular bioeconomy has been recognized as a possible solution for developing production and consumption systems that are sustainable, as well as helping to achieve the Sustainable Development Goals (SDGs). Experiences from Finland, Sweden, France, Germany, and the Netherlands illustrate that the principles of the circular bioeconomy are strongly aligned with the energy transition and deeply connected to the SDGs.

The EU's environmental policies have led to new technologies, social programs, and business models that benefit society. The goal is to use and manage natural resources in a way that is good for the environment and does not harm people. This means that companies must reduce solid waste and pollution. This policy also tries to fix problems in the market, like giving money to fossil fuels. These subsidies have shown their failure by stimulating excessive consumption and generating more externalities.

Although the circular bioeconomy is considered a viable alternative, it is necessary to recognize the specificity and context of every country to achieve harmonious development based on the natural capital, cultural diversity, and productive capacities of each territory. Furthermore, its isolated application often reproduces linear patterns if it is not articulated with circular principles. The circular economy offers a comprehensive approach aimed at redesigning production processes, reducing waste, and restoring ecosystems.

Regardless of its enormous potential to contribute to sustainable development, the circular bioeconomy faces several structural, institutional and cultural challenges that hinder its large-scale implementation. First, there is a lack of clear and shared definitions of the term circular bioeconomy among stakeholders, which creates conceptual ambiguity and hinders its consistent integration into policies, regulatory frameworks, and sectoral strategies. This conceptual ambiguity also complicates the delineation of the boundaries and scope of the circular bioeconomy in relation to other approaches, such as the green economy, the traditional bioeconomy, or the circular economy.

Second, there is a critical lack of specific, standardized, and comparable indicators to monitor and evaluate the performance of circular bioeconomy initiatives in environmental, social, and economic terms. This absence of appropriate metrics prevents us from assessing their real contribution to reducing emissions, restoring ecosystems, creating green jobs, or making rural areas more resilient. It is difficult to justify investments, scale up successful projects, or generate evidence for data-driven decision-making without robust measurement instruments.

For that reason, the objective of this paper is to analyze the fundamental principles and concepts of the circular bioeconomy and to explore the possibilities for its development in the Mexican context. The methodology applied in this work is based on a conceptual and evolutionary analysis aimed at understanding the circular bioeconomy in its complexity and multidimensionality. Therefore, a critical review of the historical evolution of concepts associated with this field, such as sustainability, green economy, circular economy and bioeconomy, is carried out.

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This strategy is responding to the need to contextualize the circular bioeconomy as a concept under construction, emerging from the convergence of previous theoretical frameworks and practices oriented towards the transition to more sustainable development models. The study of these conceptual paths identifies the common elements, tensions and transformations that have led to the current formulation of the circular bioeconomy and provides a solid basis for its interpretation and application in contexts such as the Mexican case.

This work seeks to position itself as one of the first systematic academic approaches to the study of the circular bioeconomy in the Mexican context and to contribute to the conceptual and applied development of this approach in Latin America. Despite growing interest in the circular bioeconomy as a strategy to address environmental challenges and promote a regenerative economy, there is still an absence of research on the subject in the Latin American region, especially in Mexico.

Addressing this issue from a critical, contextualized and multidisciplinary perspective reveals an important knowledge gap. Therefore, this paper aims to contribute to the theoretical understanding of the concept and establish foundations for future research, public policies, and productive initiatives promoting a sustainable transition based on the responsible use of natural capital.

This article presents a systematic, conceptual, and evolutionary analysis of the circular bioeconomy, tracing its origins from sustainability, green economy, circular economy, and bioeconomy paradigms, and examining its relevance and implementation prospects in Mexico. A critical review of the theoretical foundations and global trends reveals the circular bioeconomy as a model under construction that aims to integrate biological resources and circular principles into regenerative and low-carbon production systems.

Furthermore, the manuscript delves into the intricate web of structural, institutional, and cultural challenges that are likely to arise in the process of adopting this model. In this regard, it is imperative to acknowledge the unique natural capital and biodiversity that Mexico possesses, as these elements are poised to emerge as pivotal opportunities in the context of the proposed model. Moreover, it underscores the significance of developing context-sensitive indicators, inclusive governance, and community-based strategies to catalyze a transformative transition.

In conclusion, the authors argue that the circular bioeconomy should be regarded as a strategic alternative to the prevailing economic models, as it possesses the capacity to foster sustainability, equity, and resilience in Mexico's developmental trajectory.

2. From classical economics to sustainability: intellectual origins and shifts

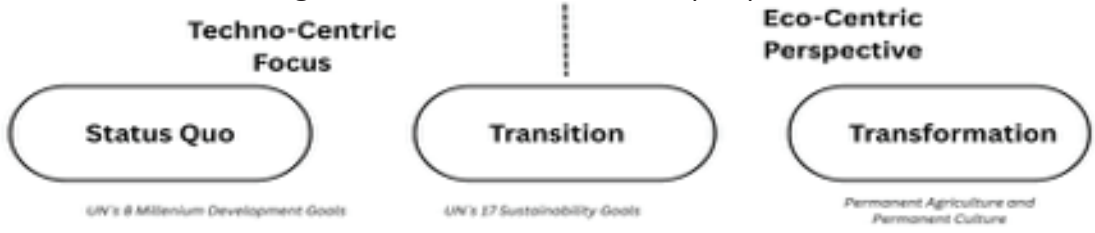
The concept of sustainable development, also known as sustainability, has emerged due to the development of different economic paradigms and the struggles of different social movements that have questioned the consequences of the dominant economic model. This model, marked by the overexploitation of natural resources and the precarization of labor, has been subject to substantial criticism for its structural unsustainability (Caradonna, 2022; Nikolaou *et al.,* 2021; Thiele, 2024).

2.1. Development and sustainability: a roadmap for systemic transformation

In this context, the modern concept of "development" was consolidated after World War II, particularly with the implementation of the Marshall Plan, which aimed to revive the European economy through financial incentives. Later, this approach was extrapolated to the countries of the Global South - in Africa, Asia and Latin America - under the premise of replicating the Western world's model of progress, centred on technological expansion and human capital (Löwy, 2018).

From this techno-centric vision, it was assumed that technological progress, innovation and economic growth would be sufficient tools to solve challenges such as poverty, resource scarcity and environmental degradation (Figure 1).

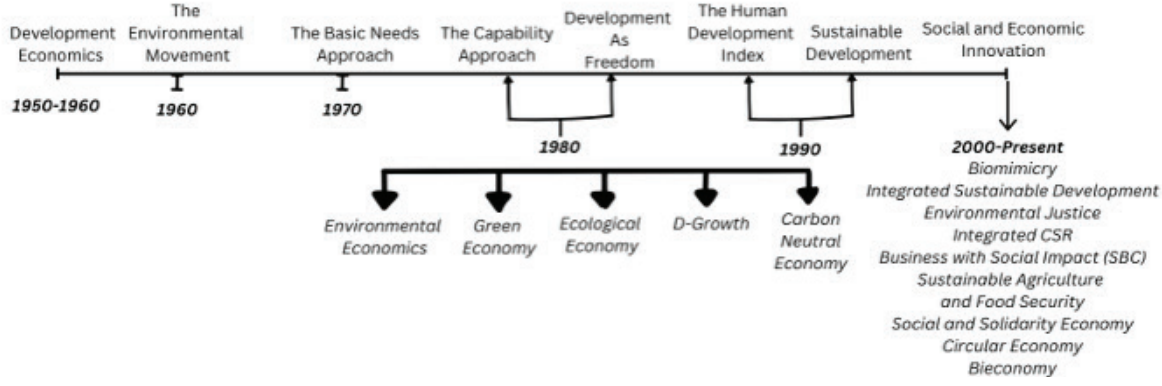
Figure 1. *Techno and Eco centric perspectives*



Source: Own elaboration based on Thiele (2024)

However, despite its objectives at the beginning, the dominant development model generated a series of negative impacts that caused the emergence of social movements critical of its efficacy and sustainability (Figure 2).

Figure 2. *Development and sustainability pathway*



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The environmental movement emerged in the 1960s, driven by growing concern about the consequences of industrial development, such as pollution and the intensive exploitation of natural resources. Although precedents existed in conservation, it was at this stage that modern environmentalism was consolidated as a social and political force of global scope (Table 1).

Table 1. *Key milestone works*

Author	Title	Contribution
Carson (1962)	Silent Spring	She founded modern political ecology, denouncing the impact of pesticides on human health and ecosystems, promoting nature as vulnerable to human intervention, and awakening environmental awareness at a massive level.
Commoner (1971)	The Closing Circle	He established the "four principles of ecology" and warned that technological advances were the main cause of environmental deterioration. He viewed technological progress from a systemic and critical perspective.
Ehrlich (1968)	The Population Bomb	He warned that population growth put natural resources and the environment in peril, possibly causing food crises and environmental collapse. Despite his deterministic perspective being challenged, his research influenced discussions on sustainable global growth.
Bookchin (1962)	Our Synthetic Environment	He criticizes the modern urban model, arguing that the environmental crisis cannot be understood without considering social structures of power and domination. From this, he developed the concept of social ecology, which links ecological problems to social inequalities.
Schumacher (1973)	Small is Beautiful	He proposed a human-scale, sustainable, decentralized economy. He also emphasized the importance of ethics and culture in economic design. His ideas had a big impact on degrowth thinking.

Source: Own elaboration

In the 1970s, global inequality grew, and people were dissatisfied with development. In response, the basic needs approach emerged. It shifted the focus from economic growth to meeting people's basic needs, especially in poor countries (Reader and Brock, 2024). The International Labor Organization (ILO) promoted this idea, especially after the 1976 World Employment Conference. At the conference, the ILO said that development should focus on guaranteeing access to essential goods like food, housing, education, health, and transportation.

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In the decades that followed, Sen (1999) radically transformed development thought by proposing an approach that focused on expanding people's real freedoms as the central goal of social progress. Rather than confining development to economic growth, Sen suggested that it should be measured in terms of people's actual ability to choose and live the lives they find valuable.

This vein, known as the capabilities approach, introduced an ethical and pluralistic dimension to the analysis of well-being by integrating elements such as health, education, political participation, and personal autonomy as fundamental pillars (Sen, 1999). This perspective significantly influenced international organizations such as the United Nations Development Program (UNDP), which adopted it as the conceptual basis for the Human Development Index (HDI). Consequently, Sen's approach succeeded in turning the traditional approach based on economic indicators into a perspective centered on human dignity, social justice, and substantive freedoms.

On the other hand, the environmental economics approach to sustainable development derives from theories of economic growth that have examined how production and consumption can be sustained indefinitely despite the existence of limited natural resources (Tietenberg and Lewis, 2023). While acknowledging the adverse externalities resulting from economic activities, such as pollution, this approach does not advocate for the restriction of economic growth (Meade, 2024).

Instead, it operates under the assumption that natural resources can be substituted by artificial or human-made resources. From this perspective, sustainability is predicated on the high substitutability of natural capital for technological capital (Myers, 2022; Setioningtyas *et al*., 2022; Berta *et al*., 2021).

This point of view is often called "technological optimism," which is the belief that technology will solve environmental problems without changing the economy much. But when environmental limits are looked at only from an economic point of view, environmental economics often forgets that not all natural resources are the same or can be used in place of each other.

A critical aspect of environmental economics is the recognition that certain natural resources are indispensable due to their capacity to provide indispensable and non-substitutable ecological services, including climate stabilization, erosion control, water and air purification, pest control, and waste detoxification (Anderson, 2019; Stavins, 2007).

The green economy is a different approach. It tries to link economic growth with environmental sustainability and social equity. It is based on the idea that it is possible to promote economic development without hurting ecosystems. This can be done by recognizing natural resources as part of a nation's capital and investing in sustainable sectors such as clean energy, organic agriculture and resource efficiency (Cato, 2012; Zhironkin and Cehlár, 2022).

A more comprehensive measurement system that considers both human well-being and the health of ecosystems is proposed by the green economy, in contrast to traditional models that focus on indicators such as GDP (Stern, 2007; Hu and Zheng, 2023). In the new scenario of climate change, accelerated biodiversity loss, and growing inequalities, this approach has become increasingly relevant as a transition strategy towards a more balanced and resilient development model (Zvarych *et al*., 2022; Hanley *et al*., 2019).

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In a similar vein, ecological economics holds that the current model of economic growth has exceeded the limits of the planet, since nature can no longer indefinitely provide the resources necessary to sustain the production and consumption processes of the current economic system. From this perspective, the Earth is regarded as a finite system, incapable of sustaining unlimited economic growth (Mastini *et al*., 2021).

Whereas environmental economics tends to adopt a techno-optimistic stance by relying on the substitution of natural resources by technology, ecological economics is characterized by a more critical or techno-pessimistic view (Costanza *et al.,* 1997; Mohan *et al*., 2019). It integrates ecological principles into its economic analysis and posits that natural capital is intricate and not wholly substitutable.

It acknowledges that not all natural resources possess equivalent value or function; some are classified as critical resources due to their provision of indispensable services for life, including clean air, erosion protection, waste detoxification, pest control and water purification, which cannot be replicated by human technologies (Daly and Farley, 2011; Common and Stagl, 2005).

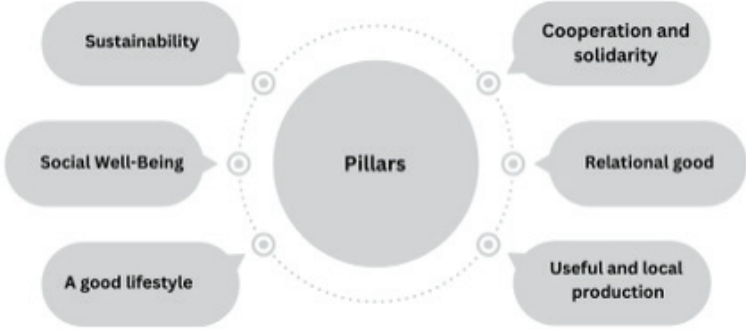
This approach necessitates a rethinking of development in relation to ecological limits, proposing a structural transformation of the economic system towards models that are regenerative, resilient, and nature-friendly, thereby engendering more balanced and resilient development.

The notion of degrowth was developed based on these principles and the proposals of the social and environmental movements of the past decades (Latouche, 2004). This term does not merely signify the absence of growth; rather, it asserts that growth is an integral component of the prevailing socio-environmental challenges, rather than a panacea (Kallis and Kallis, 2018).

It's more than a model; it's a political idea with significant theoretical consequences. Faced with the crises caused by conventional development, it proposes a voluntary and orderly transition (prosperous way down) away from growth without triggering a systemic collapse (Akbulut, 2021).

A central tenet of degrowth is the promotion of a smaller, more equitable and democratic economy, particularly in countries that have surpassed their ecological limits (Figure 3). This vision advocates for a society that prioritizes quality of life, cooperation and solidarity, as opposed to the pursuit of quantity, competition, and excessive consumption (Kallis *et al*., 2020).

Figure 3. *Fundamental principles of degrowth*



Source: Own elaboration

It revives ideals such as the Aristotelian concept of the good life. It is founded on an ethos of frugality or voluntary simplicity, emphasizing economic relocation and development on a human scale (Hickel, 2020). This approach also champions the ideal of a modern subsistence society, where individuals have reduced reliance on the market and instead prioritize the strengthening of community interdependence (D'Alisa *et al*., 2014).

The low-carbon economy is proposed as an alternative to the traditional emissions-intensive growth model, promoting a transition to production systems with a reduced environmental impact, as established by the Paris Agreement (COP21). This economy rejects the dominant consumerist logic (Pan *et al*., 2022; Wang *et al*., 2022) and proposes a development model that addresses the climate crisis without sacrificing economic welfare.

Nevertheless, from the degrowth perspective, this technological transition, while essential, is insufficient in the absence of a profound shift in consumption patterns, production methods, and cultural values. The degrowth paradigm seeks to challenge the assumption that it is possible to sustain unlimited prosperity on a finite planet, even under low-carbon models, and suggests that the solution lies in reducing the size of the economies of the global North, redistributing resources and promoting more austere, supportive lifestyles that focus on quality of life rather than material consumption (Latouche, 2004; Jackson, 2009).

In this sense, a low-carbon economy could be regarded as a preliminary phase in a more extensive process of post-growth transition, on the condition that it acknowledges the biophysical limitations of the planet and the principles of global environmental justice.

2.2. The circular economy paradigm: foundations and strategic implications

The circular economy is inspired by the principles of the green economy and proposes a profound and systemic shift in the way we understand the processes of production and consumption (Mies and Gold, 2021; Allain *et al.*, 2022). The circular economy is different from the traditional linear economic model. The traditional economic model is based on the idea of taking resources out of the earth, making products, using them, and then throwing them away.

This produces significant environmental impacts, such as the depletion of natural resources, the accumulation of waste, and the emission of greenhouse gases. The circular economy is a new way of thinking about how to use our resources better and reduce waste. It suggests using things again, recycling and remaking products.

This approach, based on sustainability, aims to keep resources in continuous use, avoiding waste and encouraging their reintegration into cycles that mimic how natural ecosystems work (Figure 4).

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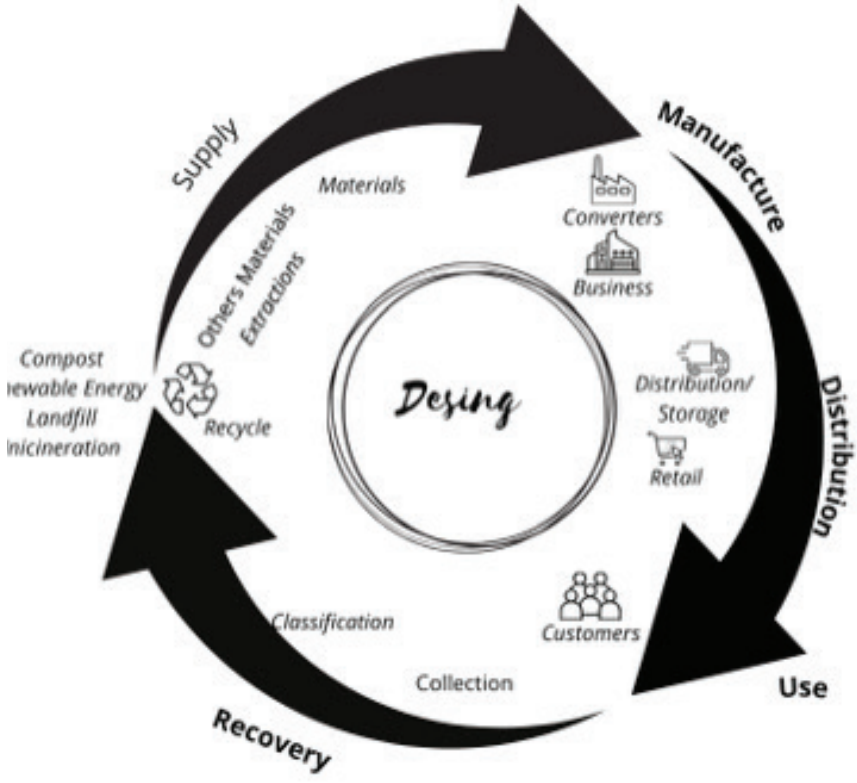
Figure 4. *Circular economy cycle*



Source: Own elaboration

The concepts of the circular economy have deep historical roots, although they have gained prominence in the last decade. One of the first examples of this idea is an 18th-century plan by François Quesnay. This plan showed how income and products could flow in a circular way, from the perspective of physiocracy, and proposed a comprehensive view of the economic system as a continuous cycle of value flows between productive sectors (Georgescu-Roegen, 1971; Dzhengiz *et al.*, 2023).

A present total of 221 definitions of circular economy have been identified (Kirchherr e*t al*., 2023). This concept, in essence, has different meanings for various actors, which has led to it being considered a term essentially in dispute. This has resulted in some consensus on the means and ends of the concept, but not so on its exact definition (Dzhengiz *et al*., 2023; Aarikka-Stenroos *et al*., 2023; Birner *et al*., 2018).

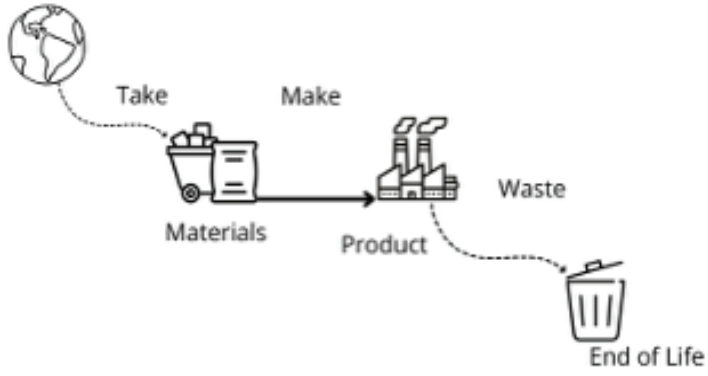
A preliminary analysis of extant definitions reveals two predominant currents within the concept. The first stream is rooted in the definition proposed by the Ellen MacArthur Foundation

(EMAF). The second is the result of the initiatives of a considerable group of scholars who emphasize the production-consumption nexus (Bugaian and Diaconu, 2020; Ratum *et al*., 2019; Gureva and Deviatkova, 2019).

The EMAF defines the circular economy as a framework for a restorative and regenerative economy by design (MacArthur, 2013). The model is based on three basic principles: a) design to eliminate waste and pollution, b) maintain products and materials in use, and c) regenerate natural systems.

The circular economy is a paradigm break from the traditional linear economic model (Figure 5). It is predicated on a productive approach that is oriented towards economic growth, decoupled from the intensive use of finite resources. The objective of the circular economy is to minimize system waste and generate positive social and environmental impacts.

Figure 5. *Linear economic model*



Source: Own elaboration

Beyond the definition proposed by the Ellen MacArthur Foundation (EMAF), various researchers have developed their own definitions, especially from the perspective of the production-consumption nexus. These definitions understand the circular economy as a sustainable development strategy focused on reducing linear flows of materials and energy.

This approach is characterized by its commitment to the efficient recirculation of resources, the incorporation of renewable energies, and the use of cascading strategies that extend the useful life of materials. A distinguishing feature of the circular economy is its emphasis on high-value-added cycles that extend beyond the conventional recycling paradigm. Furthermore, it fosters collaborative and systemic approaches between producers, consumers, and institutions with the aim of effecting a structural transformation of the socioeconomic system (Figure 6).

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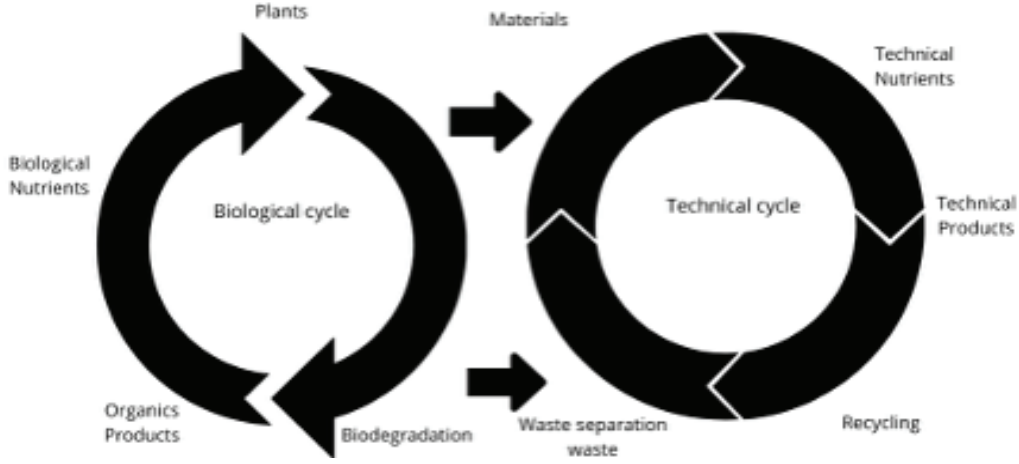
Figure 6. *Product life cycle assessment*



Source: Own elaboration

Likewise, the concept of a circular economy is frequently represented in a simplified way by the 4Rs approach: reduce, reuse, recycle, and recover. The initial three strategies are designed to minimize the use of natural resources and conserve ecological capital, while the fourth (recovery) refers to the conversion of waste into energy, as in the case of incineration.

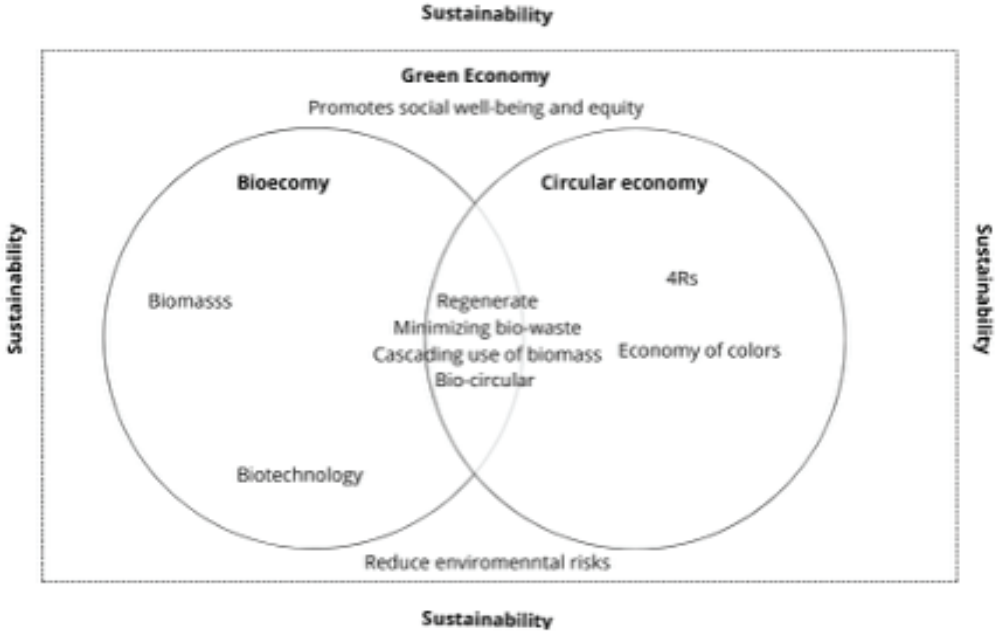
However, it has been established that, in practice, the focus of many circular economy initiatives remains economic prosperity, followed by environmental quality, while the social component of sustainability, human well-being, tends to receive less attention. The fundamental objective of this transition is to overcome the linear model of production and consumption, characterized by constant growth and increasing resource use, and to promote a decoupling between economic growth and environmental pressure.

In essence, the circular economy represents not only a technological change in production and consumption processes but also a structural transformation of the dominant economic model by integrating environmental, social, and economic principles that promote resilience, resource regeneration, and intergenerational equity. The term circular economy is used in literature and policymaking. Other related concepts that are also used a lot include biobased economy, green economy, bioeconomy, and circular bioeconomy.

2.3. The emergence of the bioeconomy: a knowledge-based economic model

The green economy is a way of integrating an economic model that seeks to improve human well-being and social equity while significantly reducing environmental risks and pressures. In simple terms, a green economy can be understood as an economy that uses resources efficiently, does not produce much pollution, and includes the social aspects of society (Figure 7).

Figure 7. *Bioeconomy context*



Source: Own elaboration

Based on this premise, the bioeconomy, like the circular economy and green economy, has emerged as a prominent field of study in recent years, gathering increasing attention from both scholars and practitioners. The term bioeconomy was first introduced in the 1920s by Baranoff to refer to the economic dynamics of the fisheries sector. In the 1960s, Zeman introduced an enhanced meaning, conceptualizing it as an economic system rooted in the biological foundations of economic processes (Bonaiuti, 2014; Lewandowski, 2018; Rojas-Serrano *et al*., 2024).

In the 1970s, Georgescu-Roegen established the theoretical basis that established the field of bioeconomics. This approach defines bioeconomics as an economic approach, based on the laws of thermodynamics, that recognizes the profound dependence of economic systems on natural resources, particularly the flows of energy and materials from the biosphere. This viewpoint highlights the physical limits of economic growth and questions the idea that economic growth is unlimited (Bonaiuti, 2014; Lewandowski, 2018; Georgescu-Roegen, 1971).

In the last decade, the bioeconomy has been a major focus in academia and professional fields. International organizations like the Organization for Economic Cooperation and Development (OECD), the United Nations (UN), and the European Union (EU) have promoted the bioeconomy. Because of the clear effects of climate change, several governments have made the bioeconomy a central part of their environmental and sustainability policies.

However, there is no universal definition of the term, which has led to discussions about

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what it includes and how it should be understood. According to the European Commission, it refers to activities that produce and transform renewable biological resources from agriculture, forestry, and aquaculture into new products with added value (Dolge *et al.,* 2023).

The German Bioeconomy Council offers a similar definition. They describe the bioeconomy as all the industrial, economic, and related service sectors that deal with the production, processing or use of biomass and biological resources in any form (Efken *et al.,* 2016).

In the United States, the Biomass Research and Development Board (BRDB) uses a different definition. It is based on a definition proposed by Golden and Handfield (2014) as part of its bioeconomy initiative. This definition says that the bioeconomy is a global industrial transition that uses renewable biological resources, like water and land, to make energy, intermediate products, and final products. This has economic, environmental, social and national security implications (BRDB, 2018).

According to McCormick and Kautto (2013), the term is understood as an economic model in which the main components of the production process are based on the use of biological and renewable resources. So, bioeconomic production uses biomass, which is made up of biological materials of plant or animal origin from renewable sources. These materials are transformed by mechanical, biomechanical, thermal, or chemical processes.

Some researchers have said that the bioeconomy is a new and effective way to turn biological resources into goods and services in different economic areas. They also say that it can be used in a way that is good for the environment. These contributions recognize the importance of the bioeconomy for sustainable development and the preservation of quality of life. It also highlights its role as a catalyst for technological innovation.

There are many definitions of the bioeconomy, and it has changed a lot since it was first described by Georgescu-Roegen. These changes have led to two main ideas that are important today. This approach concentrates on the efficient use of different types of biomasses with the aim of gradually replacing fossil fuels and promoting a more sustainable and environmentally responsible production model (Table 2).

Table 2. *Perspectives of the bioeconomy*

Component	Biotechnological view	Biomass view
Origin	1990s and 2000s	2010s
Core	Biotechnology	Value generation from innovation Biomass as a strategic input
Framework	Knowledge economy	Fossil resource substitution

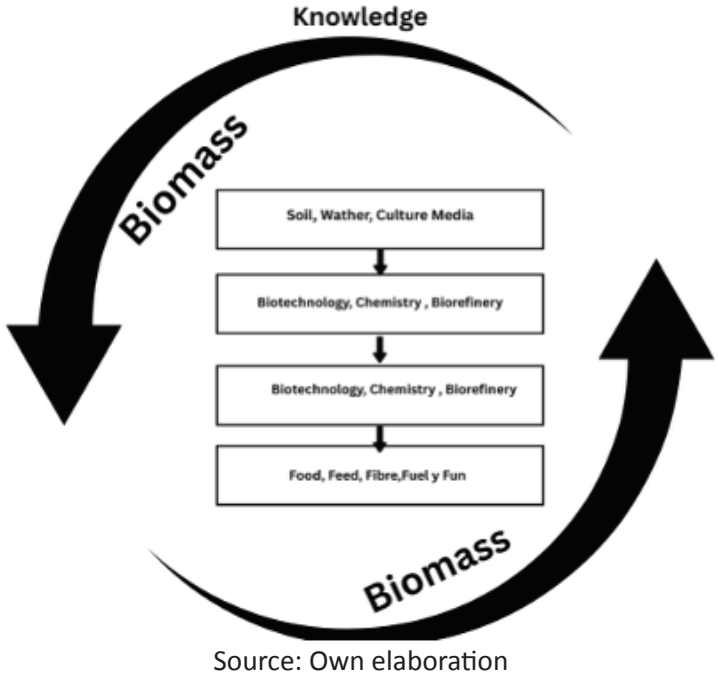
Sector	Biotechnology, scientific research, pharmaceutical.	Agriculture, forestry, fisheries, energy, chemicals.
Objective	Value generation from innovation	Sustainable production by biorefineries
Technological orientation	High intensity in biotechnology R&D	Physical, chemical and biological processing of biomass

Source: Own elaboration

The bioeconomy is distinguished from other economic approaches by its foundation on the living reality of the economy and society. While it was initially associated principally with agricultural and livestock activities, the bioeconomy has since diversified to encompass sectors linked to processing, industry, transportation, trade, and consumption. This diversification is driven by scientific research and innovation.

On the other hand, the biomass bioeconomy has emerged as a fundamental pillar in the structuring of value chains. In this model, products derived from the primary production of biomass advance through transformation, distribution, and marketing processes until they reach the end consumer in the form of food, biomaterials for industrial uses, and bioproducts for consumption (Figure 8).

Figure 8. *Biomass bioeconomy-based value chain*



Source: Own elaboration

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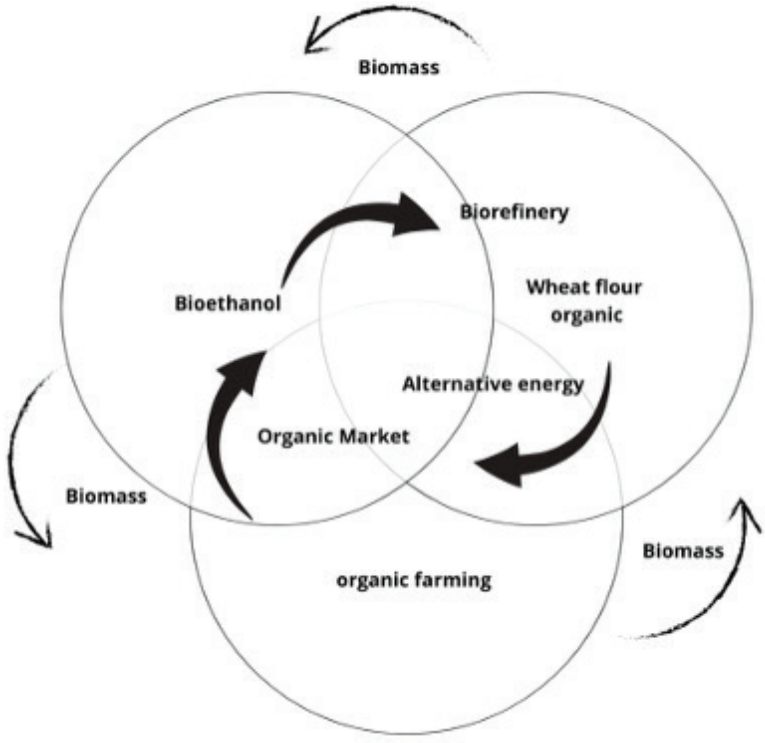
The biomass bioeconomy's fundamental purpose is the generation of biomass, a renewable resource that provides the basis to produce food, feed, bioproducts, and biofuels. Biotechnology, various chemical technologies, and specialized physical processes play a decisive role in transforming this biomass into more sophisticated and higher value-added products (Mougenot and Doussoulin, 2022; Vogelpohl and Töller, 2021; Aguilar and Twardowski, 2022).

Therefore, biomass bioeconomy-related activities can be divided into several categories (Lewandowski, 2018): a) activities based on the direct use of biological natural resources, b) activities that provide biomass for further processing, c) conventional manufacturing processes that transform this biomass, and d) innovative activities that focus on advanced processing of biomass and/or biomass-derived residues (Figure 9).

Figure 9. *Closed-loop bioeconomy system based on biomass valorization*



Source: Own elaboration

Moreover, the biomass bioeconomy is acknowledged as a pivotal element within sustainable patterns of production and consumption, acquiring mounting pertinence at the national level, within the European Union, and on a global scale. Furthermore, the biomass-based bioeconomy is increasingly recognized as a fundamental element of sustainable production and con-

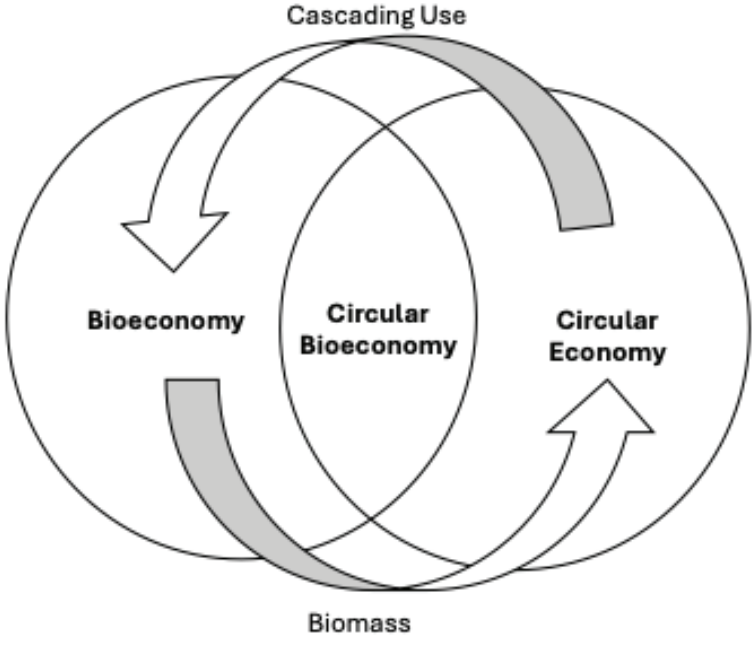
sumption systems, playing a critical role in the global transition toward low-carbon and circular economies. Its importance is steadily growing at multiple levels (nationally, within the European Union, and worldwide) as countries seek to reduce dependence on fossil resources, mitigate climate change, and promote resource efficiency (Adamowicz, 2017).

The conversion of organic waste and renewable biological resources into energy, materials, and high-value products is a key aspect of the biomass bioeconomy, which contributes to environmental sustainability, economic development, and rural revitalization. Policy frameworks such as the European Green Deal and national bioeconomy strategies further underscore its strategic significance for achieving long-term ecological and socio-economic goals (Adamowicz, 2017, Richter *et al*., 2025).

2.4. The circular bioeconomy: concepts, principles and gaps.

Based on the above, it is possible to affirm that the circular economy and the bioeconomy maintain a strong relationship, linked mainly by their common focus on addressing the environmental challenges arising from climate change and population growth (Figure 10).

Figure 10. *The link between circular and bioeconomy*



Source: Own elaboration based on Muscat *et al*. (2021)

The circular bioeconomy is an innovative approach that combines the bioeconomy and the circular economy. Its goals are to promote sustainable development. It is based on the effi-

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cient and responsible use of renewable biological resources (biomass, organic waste, crops, microorganisms and industrial by-products) to produce food, energy, materials, and high-value-added products in a way that regenerates natural ecosystems (Schipfer *et al*., 2024).

In terms of its objectives, the circular economy promotes a more efficient use of resources and materials by applying the 4R approach (reduce, reuse, recycle, and recover), which contributes significantly to reducing the use of fossil carbon. The circular bioeconomy, on the other hand, focuses on replacing fossil carbon with renewable carbon from biomass and bio-based natural resources. Although both perspectives respond to different logics and mechanisms, they are considered complementary in the transition towards a sustainable development model (Muscat *et al*., 2021).

The circular bioeconomy is the combination of the bioeconomy and the circular economy. This idea has become a popular and important approach in industry, academia, and policy-making (Schipfer *et al.*, 2024; Tan and Lamers, 2021). This forward-looking approach suggests an integrated strategy for sustainable resource management and economic development. It does this by transforming the way societies see and use renewable bio-based resources (Salvador *et al*., 2021; Schipfer *et al*., 2024; Vivien *et al*., 2019).

The circular bioeconomy is different from the traditional circular economy. It includes parts of the bioeconomy, such as using biomass and biotechnology to make goods, services, and energy (Schipfer *et al.*, 2024). Biorefineries are a key part of the circular bioeconomy. These are advanced facilities that turn biomass into many valuable products. This helps reduce the use of fossil fuels in the economy.

Unlike the traditional bioeconomy, which only uses biological resources, the circular bioeconomy also works to reduce waste, reuse and recycle materials, and extend the life of products. The goal is to rely less on fossil fuels, reduce environmental damage, and make the economy and the environment stronger.

Some experts (Kardung *et al*., 2021; Holden *et al*., 2023; Ubando *et al*., 2020) have said that we need to develop and integrate circular economy principles within the bioeconomy framework. The circular bioeconomy shares some ideas with the circular economy, but it's different because it includes specific bioeconomy things, like using biomass and biotechnology to make goods, services and energy (Figure 11).

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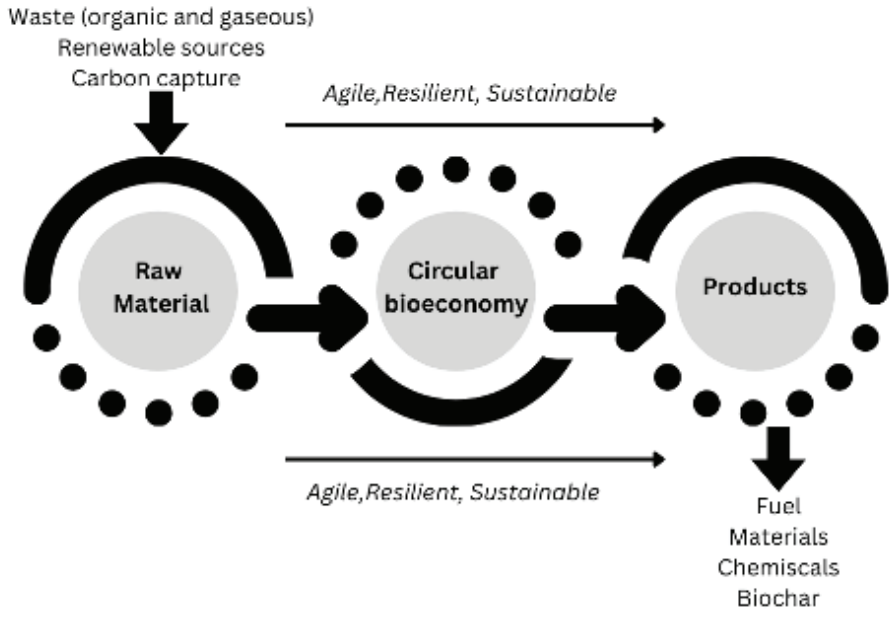
Figure 11. *Circular bioeconomy*



Source: Own elaboration based on Schipfer, *et al.* (2024)

Some studies have argued that combining these two approaches is key to addressing today's global challenges (Kardung *et al.*, 2021; Holden *et al.*, 2023). A key part of a circular bioeconomy is using biomass as a source of carbon and renewable energy. This is used to make bio-based products in advanced industrial complexes, also known as biorefineries (Leong *et al*., 2021; Kumar Sarangi *et al.,* 2023). However, there are still important gaps in the research, especially when it comes to using business models that are part of a circular economy in the bioeconomy (Muscat *et al*., 2021).

Research is needed to improve the management of bio-based renewable resources using circular principles to make productive systems more efficient, resilient, and sustainable (Muscat *et al.*, 2021). These gaps show that it is urgent to connect the circular economy and the bioeconomy (Table 3). This connection should be made in technical, systemic, and intersectoral ways. This will help create sustainable development models.

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Table 3. *Key gaps in circular bioeconomy*

Gap	Description	Opportunities
Framework and indicators	Lack of comprehensive frameworks and understanding of relevant indicators for the circular bioeconomy. This gap hinders the effective application of circular bioeconomy principles in bio-based products.	Need for tailored sustainability indicators and a specific set of indicators to foster a more integrated approach to sustainability assessment.
Standardization and Monitoring	The transition to a circular bioeconomy is complex, involving environmental and social risks. There is an uneven distribution of indicators among sustainability pillars and a lack of standardized monitoring frameworks, particularly at regional and product levels.	Generating and standardizing regional and global indicators to monitor actions taken and goals achieved.

Source: Own elaboration based on Muscat *et al*. (2021)

Therefore, there is still no clear and consistent way to identify, design and apply specific indicators for the circular bioeconomy. This makes it hard to know how well the bioeconomy is doing and what problems it is facing. This lack of structure has also made it difficult to fully understand these indicators and include them in the decision-making processes at the industrial and political levels. This makes it hard to standardize and effectively monitor them.

For this reason, it is necessary to deepen the ways the circular economy and the circular bioeconomy work together, since the identified gaps refer to the efficient management of renewable resources of organic origin. Therefore, it is important to create studies that combine different fields of study to understand the complexity of the issue and to combine technological and socio-economic views to ensure sustainable development.

According to Gursel *et al*. (2023), the biological part needs more careful study of important cycles in nature (like the cycles of carbon, nitrogen, and phosphorus) because we don't yet understand them in the context of bioeconomical systems. This is a problem for environmental policymakers and companies that want to achieve full circularity in biological flows.

The bioeconomy concept and model, although still in the process of construction and consolidation, represent a promising alternative to the hegemonic economic model, offering new ways to address contemporary socio-environmental challenges. It is all-encompassing, which means it can change how we produce things to be more sustainable (Frisvold *et al*., 2021; Richter *et al*., 2025).

It has the potential to profoundly impact various aspects of society, including the way governance is conducted, the development of novel technologies, patterns of consumption, and the operation of businesses. Consequently, these shifts, when taken together, have the potential to profoundly alter the functioning of the economy. The objective is to cultivate an economically prosperous and environmentally sustainable paradigm.

3. Mexico's Circular Bioeconomy Outlook

The circular bioeconomy has emerged as a promising approach to balancing economic development with environmental sustainability. The integration of bioeconomy principles, emphasizing the sustainable use of biological resources, with the systemic logic of circularity, which seeks to complete material and energy cycles, offers a pathway to a regenerative and low-carbon economy. For a country like Mexico, endowed with extraordinary biodiversity and a rich variety of ecosystems, the circular bioeconomy represents both an opportunity and a challenge.

3.1. Mexico's natural capital: biological diversity and conservation challenges

Mexico is considered one of the world's most megadiverse countries, hosting approximately 12% of global biodiversity. It possesses over 200 ecosystems, spanning forests, deserts, mountains, and coastlines (CONABIO, 2016). This natural wealth is matched by a significant biological productive base, with agriculture, forestry, and fisheries contributing nearly 4% to Mexico's GDP and employing over 12% of the national labor force (INEGI, 2022).

This biological wealth provides vital ecosystem services that support not only environmental integrity but also key sectors of the national economy. These services include carbon sequestration, water regulation, pollination, soil fertility, erosion control, and natural disaster mitigation. The agricultural sector, which employs approximately 12% of the national workforce, is highly dependent on the ecological functions sustained by healthy soils, freshwater systems, and pollinator populations (INEGI,2022).

Tourism, which contributes over 8% of Mexico's GDP (INEGI, 2022), is also heavily reliant on natural landscapes and biodiversity hotspots such as coastal reefs, forests, and protected natural areas. Forest ecosystems provide a source of livelihoods through timber, non-timber forest products, and carbon markets, especially in communities engaged in sustainable forest management programs.

Despite its natural wealth, Mexico is experiencing increasing pressure on its natural capital. The nation experiences an estimated annual deforestation of 150,000 hectares, primarily attributable to agricultural expansion, urbanization, and illicit logging practices (CONAFOR, 2020). Wetlands and mangroves are being degraded by the development of tourism infrastructure, pollution, and aquaculture activities. The Mexican government currently lists more than 2,500 species as endangered, with amphibians and endemic plants among the most vulnerable (CONABIO, 2016).

The nation's water resources are also under significant strain, with nearly 40% of its aquifers being overdrawn, resulting in ecosystem imbalances, particularly in arid and semi-arid regions (CONABIO, 2016). The impacts of climate change, including more frequent droughts, extreme weather events, and shifts in species distributions, further exacerbate pressures on biodiversity.

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The government of Mexico has developed a comprehensive instrument for conservation over the past decades. The establishment of more than 180 federal protected natural areas (PNAs), which cover nearly 13% of the national territory, represents a cornerstone of biodiversity policy (CONANP, 2020). However, many of these areas face challenges such as inadequate funding, limited staffing, and ineffective enforcement.

Efforts such as the Payment for Ecosystem Services (PES), administered by the National Forestry Commission (CONAFOR), have demonstrated potential in incentivizing conservation among forest-owning communities. Similarly, initiatives led by the National Commission for Protected Natural Areas (CONANP) have promoted co-management models with local actors. Nevertheless, interinstitutional coordination remains limited, and environmental policies are often not integrated into broader economic planning.

On the other hand, more than 60% of Mexico's territory is communal or ejidal, and many indigenous communities manage large areas of forests and other ecosystems. These communities possess traditional ecological knowledge that contributes to sustainable land use and conservation (CONAFOR, 2020). Nevertheless, their involvement in formal environmental governance has frequently been marginalized.

Recognizing and strengthening community-based conservation initiatives is imperative. Examples such as the forest cooperatives in Oaxaca and the agroecological practices in the Yucatán Peninsula demonstrate the effectiveness of culturally rooted, bottom-up strategies in preserving biodiversity and maintaining ecosystem functions (Reyes Heredia *et al*., 2022).

The presence of natural wealth, productive potential, and self-management capacity in Mexico's indigenous communities indicates the necessity of the implementation of public policy strategies that integrate natural capital into sustainable economic activity.

3.2. Circular Bioeconomy: an opportunity for Mexico?

The transition toward a circular bioeconomy represents a strategic and timely opportunity to integrate natural capital more effectively into Mexico's production systems. This paradigm shift involves replacing linear, fossil-based models with regenerative systems that emphasize the sustainable use of biomass, the restoration of ecosystem functions, and the closure of material and energy loops (Secretaria de Medio Ambiente y Recursos Naturales, 2020).

In the Mexican context, characterized by exceptional biological wealth that is simultaneously under threat, this model demonstrates the potential to reconcile environmental conservation, scientific and technological innovation, and inclusive socioeconomic development.

Mexico's considerable natural capital, comprising fertile soils, hydrological basins, forest resources, and a substantial degree of terrestrial and marine biodiversity, represents a pivotal asset for the promotion of a regenerative circular bioeconomy (World Bank, 2021).

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Conventional economic planning has historically underestimated or externalized this capital. The circular bioeconomy aims to address this imbalance by incorporating ecosystem services into productive processes as quantifiable and strategic assets.

From an economic perspective, the circular bioeconomy is a system that utilizes agricultural, forestry, and organic byproducts in a sustainable manner to produce bioenergy, bioplastics, biofertilizers, and high-value biochemicals. It also promotes the agroecological transformation of productive systems, the valorization of agricultural by-products, and the low-carbon reindustrialization of strategic sectors such as agri-food, forestry, and fisheries. These practices contribute to environmental restoration and rural development, and their progress can be tracked through key indicators, including

1. Biomass valorization ratio (percentage of total biomass waste reintegrated into productive processes),
2. Carbon sequestration capacity (measured in CO_2-equivalent tons captured through agroforestry or regenerative agriculture),
3. Soil health indices (e.g., organic matter content, nutrient cycling rates),
4. Circular input rate (share of recycled or bio-based materials in production),
5. Biodiversity richness index in managed landscapes,
6. Water reuse and efficiency rates in agricultural and industrial systems, and
7. Rural employment generation in bio-based value chains.

The successful integration of natural capital into a circular bioeconomy framework requires robust institutional infrastructure and enabling policy instruments. The relevant factors include

1. Environmental accounting systems that reflect the true ecological cost and value of ecosystem services;
2. Biomass traceability and certification mechanisms to ensure sustainable harvesting and use;
3. Regulatory frameworks that incentivize circular design, eco-innovation, and extended producer responsibility;
4. Fiscal incentives and public procurement policies favoring bio-based and circular products;
5. Monitoring and evaluation systems using indicators such as the Bioeconomy Contribution Index (measuring the share of GDP and employment from circular bio-based sectors) and the Circular Material Use Rate (CMUR) adapted to biomass flows.

Empirical evidence from localized initiatives, such as silvopastoral systems in Oaxaca, community forest enterprises in Michoacán, and emerging biorefinery clusters in Jalisco, underscores

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the potential of circular bioeconomy models rooted in local ecological knowledge, technological adaptation, and sustainable resource governance (Reyes Heredia *et al.*, 2022).

These initiatives are indicative of a significant yet frequently overlooked strength of Mexico: its capacity for place-based innovation driven by community agency, cultural traditions, and ecological stewardship. In particular, the ejido and communal land systems provide institutional frameworks through which bioeconomy practices can be grounded in long-term resource management, collective benefit sharing, and localized decision-making. These grassroots experiences have successfully demonstrated the integration of biodiversity conservation, rural employment, and climate resilience within bio-based value chains.

However, the current bioeconomy landscape in Mexico remains fragmented, with limited articulation between national policies and territorial realities. While the federal government has acknowledged the relevance of the bioeconomy through strategic documents such as the National Bioeconomy Plan (Plan Nacional de Bioeconomía) and the Sectoral Program for Agriculture and Rural Development (2020–2024), these efforts remain largely technocratic and insufficiently aligned with circularity principles or community-based governance models.

Furthermore, most policy instruments prioritize biotechnology, agribusiness competitiveness, and export-led growth rather than emphasizing circular material flows, ecosystem regeneration, or social equity.

The successful implementation of localized models necessitates a paradigm shift in public policy and governance. This includes the reinforcement of multi-level governance mechanisms that connect federal institutions with municipal and community governance systems, the promotion of policy coherence across environmental, agricultural, and innovation sectors, and the acknowledgement of the ecological and economic value of ecosystem services through national accounting systems.

The emergence of a coherent circular bioeconomy agenda is hindered by institutional constraints, including weak interagency coordination, limited territorial planning capacity, and the exclusion of Indigenous and campesino voices from formal consultation processes. Moreover, inadequate access to financial resources, regulatory flexibility, and investment in research and development focused on small-scale bio-based innovations persist as challenges.

Moreover, the pressing nature of the climate and biodiversity crises underscores the need for a more transformative approach to the bioeconomy. This approach must move beyond mere technological substitution and shift towards the development of regenerative socio-ecological systems. In this regard, the circular bioeconomy offers not just a productive reconfiguration but a normative reorientation of economic models, grounded in environmental limits, intergenerational justice, and biocultural diversity.

In conclusion, the circular bioeconomy in Mexico must be conceived not merely as a niche economic sector but as a systemic transition strategy embedded in the country's rich territorial diversity and sociocultural heritage. A multisectoral and multifaceted approach is required to

realize its transformative potential. This approach must integrate scientific research, territorial governance, inclusive public policy, and responsible private sector engagement. It is imperative that this vision prioritize the active involvement and rights of Indigenous and rural communities.

The ecological knowledge, land tenure systems, and productive practices of these communities are indispensable to sustainability. It is imperative to recognize that the circular bioeconomy, when integrated and centered on equity, holds the potential to meaningfully contribute to climate adaptation, biodiversity protection, rural revitalization, and the realization of a sustainable and inclusive future for Mexico.

3.3. From waste to wealth: sector-based indicators for advancing Mexico's Circular Bioeconomy

In Mexico, the advancement of a systemic transition towards a circular bioeconomy is contingent upon the development of robust and context-sensitive indicators that capture both the progress and the potential of this transformation. These indicators should not only assess current levels of circularity and sustainability but also guide the design of policies, investment strategies, and territorial planning. A particularly strategic approach involves the identification and classification of residual biomass flows by type of bioindustry, which allows for the quantification and qualification of waste streams and their potential reintegration into productive cycles. Quantitatively, this approach demands the implementation of standardized metrics to monitor pivotal dimensions of the bioeconomy-circularity interface, including:

1. The conversion of waste into resources is measured and analyzed according to the specific sector involved, such as agriculture, forestry, fisheries, and agri-food processing.
2. The term biomass valorization indices refer to the measurement of the proportion of residual materials that are converted into bioenergy, biofertilizers, bioplastics, or biochemicals.
3. The Circular Input Rate (CIR) is a metric indicating the proportion of recycled or reused biomass within each bioindustry.
4. The potential for carbon abatement is predicated on the substitution of fossil-intensive inputs with bio-based alternatives.
5. The economic value generated per ton of biomass waste enables a comparative analysis across sectors.
6. The creation of employment opportunities in a sustainable manner, particularly within bioindustrial recovery chains and downstream processes, is a critical aspect of environmental policy.

From a qualitative approach, the development of transition indicators must also consider the following aspects:

1. The institutional and governance capacity to manage residual flows is comprised of several components, including territorial articulation, traceability systems, and local regulations.
2. The environmental co-benefits of revalorized waste streams include improved soil quality, reduced pollution, and enhanced ecosystem resilience.
3. The degree to which bioindustrial sectors incorporate R&D, local knowledge, and eco-design principles into circular strategies is indicative of their knowledge intensity and innovation potential.
4. The integration of indigenous peoples into the formal economy is achieved through their incorporation into the value chain.

A multidimensional indicator framework rooted in both quantitative metrics and qualitative assessments can function as a strategic instrument for transition monitoring, scenario planning, and adaptive policy design. This initiative has the potential to unveil the latent value inherent in Mexico's biomass waste streams and to provide a framework for the implementation of a circular bioeconomy across various sectors and regions, with a focus on social inclusion and environmental sustainability.

4. Conclusions

In response to the urgent need to move towards more sustainable, resilient, and regenerative economic models, the circular bioeconomy is emerging as a promising approach. This work shows that the circular bioeconomy is not a separate entity but rather the result of a conceptual convergence between the bioeconomy and the circular economy—both of which have evolved from earlier paradigms such as sustainability, the green economy, and ecological economics.

This analysis showed that the circular bioeconomy introduces a systemic perspective that combines the valorization of biological resources with principles of circularity, thereby overcoming the limitations of previous approaches that tended to reproduce linear patterns of production and consumption.

A persistent conceptual ambiguity surrounds the term "circular bioeconomy," which hinders its effective incorporation into public policy frameworks and regulatory instruments. Moreover, there is an absence of standardized metrics to evaluate the environmental, economic, and social performance of circular bioeconomy initiatives. The absence of metrics has been identified as a significant impediment to the effective monitoring and scaling of these systems.

The study also reveals limited institutional and territorial coordination. Rural and Indigenous communities, despite their critical role in managing biodiversity-rich landscapes, remain largely excluded from the design and implementation of circular bioeconomy strategies. However, several localized initiatives in Mexico, such as agroforestry systems, community biorefineries, and silvopastoral practices, illustrate the country's significant potential to develop inclusive and context-sensitive circular bioeconomy models.

In this context, the circular bioeconomy has the potential to offer Mexico a broad scope of quantitative and qualitative benefits. Quantitative studies from analogous regions indicate that the implementation of circular bioeconomy strategies could potentially result in the following outcomes (Rojas *et al*., 2024; Medina *et al*., 2024):

1. Increase biomass utilization efficiency by over 30%, reducing agricultural waste and improving energy recovery,
2. Generate up to 1.5 million new green jobs, particularly in rural areas, through bio-based value chains;
3. Enhance carbon sequestration by 25% in managed agroecosystems through regenerative practices;
4. Improve rural incomes by 20–40% through the diversification of circular bio-based enterprises;
5. Contribute up to 8% of national GDP if effectively scaled and integrated with existing rural development programs.

From a qualitative perspective, the circular bioeconomy fosters the following:

- Greater territorial cohesion by linking local knowledge systems with sustainable production;
- Enhanced community resilience through ecosystem restoration and food sovereignty;
- Cultural revitalization by valuing Indigenous agroecological practices and collective land management;
- Social equity through inclusive governance models and participatory innovation.

However, the study is not infallible and recognizes its own limitations. As an exploratory and theoretical contribution, it does not include empirical case studies or quantitative modeling. A salient challenge encountered during the research process pertained to the paucity of academic literature and systematized data concerning the circular bioeconomy in Mexico and Latin America. This discrepancy underscores a dual limitation and opportunity: the absence of local research emphasizes the necessity for more in-depth, context-specific studies that can inform evidence-based policymaking and fully actualize the potential of the circular bioeconomy in the region.

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