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Review

Weaving Knowledge, Innovation, and Learning: A Transdisciplinary Pathway to Circular Bioeconomy Through BioBeo

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Abstract

The bioeconomy represents a new way of life for people, but also a responsibility towards the future of the planet. Generating a significant socio-economic impact, it could be viewed as a key element of sustainable development, as the current and future solution for economic processes, based on new development models compelled by climate changes and the economy's resilience to potential crises. In this context, the paper presents in its first part the Circular Economy description and the Circular Bioeconomy discussion from an interdisciplinary perspective. The second part of the paper aims to explore education as a tool for facilitating systemic changes supporting a real transition to a sustainable bioeconomy. The key aspects discussed refer to the following: (1) European policies, strategies, and action plans for bioeconomy; (2) Circular Economy as a solution for sustainable food systems; (3) main requirements and challenges for developing a (Circular) Bioeconomy, including indicators of sustainability; (4) the links between Circular Bioeconomy and the Sustainable Development Goals; (5) possibilities for integrating the agri-food industry's needs into bioeconomy education; and (6) pathways for teach bioeconomy concepts effectively.

Keywords: circular bioeconomy; sustainable resource production; biobased alternatives; biological knowledge; sustainability transformation; education for the bioeconomy; education; research and innovation

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1. Introduction

The shift toward a circular bioeconomy necessitates a profound recognition and appreciation of the intricate interdependencies that exist, not only between humanity and the natural world but also across diverse disciplines, sectors and communities. Circular bioeconomy emphasises the sustainable use of biological resources, necessitating a holistic approach that integrates science, practice and education. Central to this transformation is a transdisciplinary framework where education serves as a key vehicle for fostering this

interconnectedness. Education is a key driver in shaping societal responses to emerging global challenges, such as climate change, environmental degradation and resource scarcity. One such response is the development of a circular bioeconomy, which is increasingly recognised as a sustainable alternative to linear economic models. The integration of a circular bioeconomy into mainstream education, as demonstrated by research such as the Horizon Europe BioBeo project [1], which built on the previous Horizon 2020 AgroCycle project [2], requires a transdisciplinary approach that bridges the science–society nexus.

A transdisciplinary approach works to integrate ways of knowing and diverse points of view to arrive at a clearer understanding of the issue presented. Secondly, a transdisciplinary approach places significant emphasis on relationship building and open communication to reimagine ideas and methods. Thirdly, a transdisciplinary approach strongly endorses and supports creative innovation and feasible solutions [3,4]. Through education and community engagement, the principles of the circular bioeconomy can be embedded in society, creating a ripple effect that extends beyond the classroom and into the wider world.

Successful transdisciplinary approaches rely on science communication that recognises concepts but also respects social situations, such as traditions or the way a community is organised and includes same in the co-creation process of a common understanding of a science-based concept such as a circular and sustainable bioeconomy. This is especially important because bioeconomy is a place-based concept [5–7].

This paper explores the intricate scientific knowledge underpinning the circular bioeconomy and demonstrates the essential role of collaborative, pedagogical approaches in translating this complexity into accessible education. By employing a pedagogy of love, specifically a relational pedagogy, education can foster a deep sense of connection, encouraging communities to adopt bioeconomic practices, and live in harmony with nature embracing a sense of love and respect for the environment. This approach is particularly relevant in the context of circular bioeconomy education, as it allows for the integration of complex scientific and social concepts in ways that are both comprehensible and actionable.

A Note on the Understanding of Bioeconomy

The Bioeconomy Strategy was updated in 2018, aiming to maximise the contribution of European Bioeconomy towards the 2030 Agenda and its SDGs. According to this updated Bioeconomy Strategy, "the bioeconomy covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), their functions and principles" [8]. The EU Bioeconomy Strategy Progress Report "European Bioeconomy policy: stocktaking and future developments" was published in 2022 [9].

Bioeconomy solutions and future concepts are requested to build on biomass feedstocks that do not compete with food security and will not increase the pressure on land or natural ecosystems. This is an example of why, at the core of a sustainable and circular bioeconomy, the valorisation of by-products and waste streams and the recovery of valuable chemicals from different sources is incremental to ensure a more efficient use of resources. Thereby, creating more sustainable and resilient supply chains and new business opportunities, especially for those at the beginning of the supply chain.

The concept of circularity within a bioeconomy can be better understood when referring to the waste hierarchy or waste framework directive. "It requires that waste be managed-without endangering human health and harming the environment, without risk to water, air, soil, plants or animals, without causing a nuisance through noise or odours and without adversely affecting the countryside or places of special interest" [10]. Although this concept is not directly targeted at biomasses per se, it can also be extended to various other non-organic wastes, providing fundamental understanding of how to approach by-

products and achieve a future where by-products or wastes are no longer seen from this perspective. The overall goal is to achieve a world where we find resources with distinct properties which are to be treated with responsible foresight to understand which part of each virgin resource will be used, why it will be used, and when. All cascading uses of biomass must be designed with consideration for the material's end-of-life stage, ensuring that mechanisms are in place to enable the closure of the resource loop. This approach embodies the fundamental concept of "circularity" within the term circular bioeconomy. Accordingly, a circular bioeconomy aligns with the core principles of the Waste Framework Directive, prioritising the extension of product lifespans and the reuse of biobased materials. In this hierarchy, energy recovery is regarded as a final resort, only to be pursued once all viable material applications of biomass have been exhausted.

A successful bioeconomy needs coherent and integrated policy direction [11], which possesses a skilled workforce as one of its key areas. To achieve this desideratum, it is essential that the bioeconomy be integrated across all levels of the education system—primary, secondary and tertiary—in order to cultivate awareness, build competencies, and ultimately render careers in bioeconomy-related sectors more attractive and accessible. This comprehensive educational approach is pivotal for developing a skilled workforce capable of supporting and advancing a sustainable circular bioeconomy The sixth recommendation of the White Paper, entitled Education and Training [11], suggests developing an Education Action Plan (EAP) by involving all relevant stakeholder groups. The main aim of this EAP is to inform the decisional and operational structures about the future needs of the bioeconomy for a well-qualified workforce.

Attracting youth to STEM (Science, Technology, Engineering, and Mathematics) disciplines and cultivating their multidisciplinary skills needed for a future workforce in economic activities derived from biotechnology and bioprocessing demands special approaches [12]. The cooperation of academia, industry, and government within developed informal education platforms could be an innovative way to meet the global needs, including addressing the lack of youth interest in STEAM. Bioeconomy education should successfully address societal and technological developments, such as climate-smart forestry and increasing digitalisation of forest measuring strategies if forest bioeconomy is discussed [13] or uses of avoidance of food loss as suitable biomass for human food products with high market attractiveness [14] when environmental and economic benefits are targeted.

Three types of knowledge were identified as cognitive spaces for addressing the problems raised by the bioeconomy concept, namely systems knowledge, normative knowledge and transformative knowledge [15]. An overview of educational approaches for the bioeconomy emphasises that they are generally problem-based and interdisciplinary and combine academic and experiential ways of knowing [16]. Building on the foundation established by the AgroCycle project, the BioBeo project has advanced the integration of circular bioeconomy principles within education and community engagement. Emphasising transdisciplinary collaboration, BioBeo seeks to embed circular bioeconomy concepts into formal and informal education, enhancing scientific literacy and sustainability awareness across age groups. Supported by the European Commission through Horizon funding, the project employs experiential learning and real-world case studies to make bioeconomy knowledge accessible—from primary education to policy-making spheres. This approach fosters a scientifically grounded understanding of resource efficiency and sustainability, while empowering individuals to enact systemic change within their communities.

2. Literature Review

2.1. Short Overview on Circular Economy

The world is in the throes of rapid demographic growth, with employment opportunities coming from the continuous trends of industrialisation and urbanisation. A circular economy can create economic opportunities and employment, while avoiding a range of negative externalities resulting from the old linear concepts of fossil-based large-scale industrialisation, heavily dependent on global supply chains.

A circular economy model considers the technical pathway as well as the biological pathway as distinct material flows. Consumption occurs in biological cycles, where residuals from food and bioproducts production and consumption derived from hemp, straw, cotton or wood are returned to the system through processes such as composting and anaerobic digestion. These cycles regenerate ecosystems providing renewable resources for healthy soils and then for the economy.

The application of the circular economy principles in the agri-food sector co-creates a societal transformation and that results in a greater ability to positively face future challenges. Production systems can become more circular through conversion to an economic system focused on saving and recovering resources. Thus, it is possible to act through an optimised supply chain or through an exchange of resources between activities considered complementary (e.g., in agriculture or animal husbandry). The last solution follows the logic of industrial symbiosis, allowing the recovery and valorisation of agricultural or animal residues to generate energy, fertilisers, and natural fibres to be shared with other production activities, encouraging the inclusion of several actors in the system and favouring closure loops to ensure circularity. Food waste recovery is necessary for the transition of the agri-food sector towards a circular economy. The proper management of food waste leads to a reduction in environmental pressures but also generates economic (value retention) and social (employment opportunities/stakeholder cooperation) benefits.

However complex this information may present itself to global citizens in mainstream society, it has a place in a global conversation to create an awareness of the possibilities in development in the world today in addressing climate change [17] and the effects of human behaviour on the earth. The optimal avenue for this conversation is through education and a transdisciplinary approach in research. To take it a step further, in living within our planetary boundaries, the focus will now shift towards a circular bioeconomy.

2.2. Circular Bioeconomy—A Closer Look

Aiming to promote scientific excellence in Europe, different EU research programmes and particularly the Framework Programmes led to an accumulation of experience that constituted in an essential prerequisite for the foundation of the bioeconomy concept the emergence of which, in the EU, has been the result of chance and necessity [18].

In 2007, the EU Commission presented the Knowledge-Based Bioeconomy (KBBE) concept [19], its vision for a European bioeconomy in 2030. This concept, which emerged in 2005, covered all economic sectors dealing with carbon-based raw materials: agriculture, fishery, aquaculture, and forestry. Later, the KBBE concept was condensed into the concept of a bioeconomy, and it evolved into the circular bioeconomy [20]. The basis of the bioeconomy strategy and action plan are the collaborative efforts of the experts involved in the EU Technology Platforms (ETPs). These ETPs covered different segments of KBBE [21], enumerating selectively only a few, such as the EU Technology Platform "Food for Life", EU Technology Platform for Sustainable Chemistry, European Aquaculture Technology and Innovation Platform, and European Biofuels Technology Platform.

The term bioeconomy was used until 2005 mainly in relation to economic activities focused on biotechnology [22]. The definitions of bioeconomy varied largely and sometimes overlapped, depending on scope and the issues concerned.

Bioeconomy means the "production of renewable biological resources and their conversion to food, feed, bio-based products and bioenergy" [21]. Bioeconomy is both a concept and a dynamically developing sector of the economy [23], that can be viewed as "a vision for the future society" [21] due to the sustainable use of bioresources. Bioeconomy is defined in the EU Bioeconomy Strategy (2018) as follows: "the bioeconomy covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), their functions and principles. It includes and interlinks land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy, and services (except biomedicines and health biotechnology)" [24].

The bioeconomy concept integrates a green bioeconomy, which is driven by the Food–Feed–Fibres crisis [21]. Waste management was identified as one of the six sectors of a green economy, the importance of which in the circular bioeconomy has become overwhelming.

Aiming to enhance the knowledge base for policymaking on the bioeconomy, a European Commission initiative, named "The Knowledge Centre for Bioeconomy" offers relevant and structured information on eight topics related to the bioeconomy concept. The eight integral topics are as follows: Economy, Policy, Forest-based bioeconomy for climate change mitigation, Fisheries and aquaculture biomass, Forestry biomass, Agricultural biomass, Assessing environmental impacts, and Algae biomass [25].

The annual bioeconomy turnover in the EU, as of 2009–2010, was estimated at over EUR 2000 billion [23]. The data for EU-27 show a continuous increase in turnover in the bioeconomy to more than EUR 2.3 trillion in 2021, of which almost half represents the contribution of the food and feed industries [26]. Employment in the sector of bioeconomy decreased over the years, from 22 million people in 2009–2010 [23] to an overall 16 million people in 2021. However, it was reported that the number of employees remained relatively stable for biobased industries [26].

2.3. How Can We Link Circular Bioeconomy with Education?

Schools and universities are uniquely positioned to cultivate eco-responsible citizenship, teaching students to challenge traditional, linear economic models and embrace sustainable practices [27]. This position is reinforced by studies emphasising that higher education institutions play a key role in shaping future professionals who can implement and advocate for circular bioeconomy solutions [28]. The systematic investigation of circular bioeconomy developments by research initiatives—and the subsequent dissemination of this knowledge to the wider public—is essential. Integrating circular economy and circular bioeconomy concepts into educational curricula can catalyze systemic change and foster a long-term shift toward sustainability-oriented thinking.

The objective of these funded research initiatives such as BioBeo was to analyse the main topics related to circular bioeconomy and their scientific concepts, and to translate this complex science for it to become accessible for educational settings at every level. There is an existing gap between the realm of economy, science, and curricula supporting bioeconomy education. There are still some observable concerns in the labour market, including the development of biobased businesses or biorefineries in certain countries and fields of activity. These concerns can be mitigated in time if education is suitably designed and implemented, but this is only possible if teachers and stakeholders interested

in education fully grasp the circular nature of a bioeconomy, the related concepts, and their application.

3. Methods and Analysis

3.1. Scientific Reporting in Relation to Circular (Bio)Economy and Education

To achieve the objectives of this study, a comprehensive review of the relevant literature was conducted.The Boolean search strategy was used for searching the literature in the prominent academic database Web of Science (WoS). We focused on specific terms from different groups: "circular economy", "circular bioeconomy", and "education". The Boolean operators "AND" and "OR" were employed. Some filters were used, namely interval of publication, type of publication, WoS categories, and sustainable development goals (SDGs).

A bibliometric analysis using VOSViewer version 1.6.20 [29] was employed to analyse the publications in alignment with the defined objectives based on the data that were extracted. The chart was created not only to comprehend the relationships that exist between circular bioeconomy and keyword co-occurrence, but also to serve as an educational tool for scholars and everybody interested in the circular bioeconomy for building a sustainable future. The goal was to fill a knowledge gap between the scientific concepts and the main topics that should be introduced in education for circular bioeconomy, with the scope to educate all ages so that they can integrate into a future, dynamic, and competitive labour market, achieving professional success.

Mapping SDGs in relationship to a circular bioeconomy was realised with a view to identify those SDGs where alignment with the implementation of circular bioeconomy is unsatisfactory at this point. Starting from this map, the factors threatening it can be identified and appropriately addressed.

The scientific information from this work was found on recognised platform such as Web of Science and Google Scholar. Specific keywords were used, namely "Circular Economy", "Circular Bioeconomy", and related terms, as they were displayed in co-occurrence with the "Circular Bioeconomy" by VOSviewer chart.

3.2. Bioeconomy Education

To bridge the science–society nexus regarding bioeconomy in education, a set of questions has been devised to address how such content can inform education at all levels. The questions pertaining to embedding bioeconomy across all education levels are as follows:

- ✓ How can we think about/rethink bioeconomy-related education considering, gaps and challenges in current bioeconomy education programmes also?
- ✓ How can we design bioeconomy curricula and meet the students' needs at all levels of education from preschool to third level?
- ✓ How do we ensure required skills for bioeconomy and/or the digital skills required for bioeconomy are embedded in education and in mainstream society?
- ✓ What are the key competences needed by students for bioeconomy understanding and application?
- ✓ How do we educate educators on the advancement of bioeconomy knowledge?

The response to these questions is outlined below in an effort to present possibilities for integrating bioeconomy into the agri-industry and education holistically for the greater good of mainstream society and of course the planet.

4. Results

Results are presented here, according to the methods and analysis introduced in the previous section. Hence, the subsections are the following: topics and trends found by literature analysis related to circular economy, circular bioeconomy and education (Section 4.1); scientific basis of the circular bioeconomy and its implementation in realm (Section 4.2); integration the work of industry and research into bioeconomy education (Section 4.3); educating teachers in bioeconomy (Section 4.4).

4.1. Literature Analysis: Topics and Trends

4.1.1. Overview of Bioeconomics Research

An inventory of publications was collated in the Clarivate Analytics Web of Science (WoS) Database for the period 1981–2025, using "circular economy" as the search term and the application of different filters to interpret the data.

The number of publications retrieved on 18 September 2024 was 30,229, more than 35% belonging to the category Environmental Sciences. The topic began to spark academic interest in 2016, with the number of publications being more than double compared to the previous year. Despite the continuous increasing of the number of scientific papers until 2023, it seems that this trend is slightly decreasing or linear, taking into account the data retrieved by WoS for 2023 (6265 publications) and 2024 (4695 publications), respectively.

The spread of publications within the WoS categories suggests the multidisciplinarity of the concept of circular economy (Figure 1). Continuing searching using terms "circular economy" and "sustainability", 9381 documents were retrieved by WoS, from which about 41% publications in the category Environmental Sciences and about 35% publications in the category Green Sustainable Science Technology. An inventory of publications was collated in the Clarivate Analytics Web of Science (WoS) Database for the period 1981–2025, progressively using search terms such as "bioeconomy", "circular bioeconomy" and "circular bioeconomy" AND "education", respectively. The topic "bioeconomy" retrieved 5974 results (articles, proceeding papers and books), while the topic "circular bioeconomy" less than half (2548 results). Only 31 publications were selected from the Web of Science Core Collection for the topic "circular bioeconomy" and "education" in period 2017–2025.

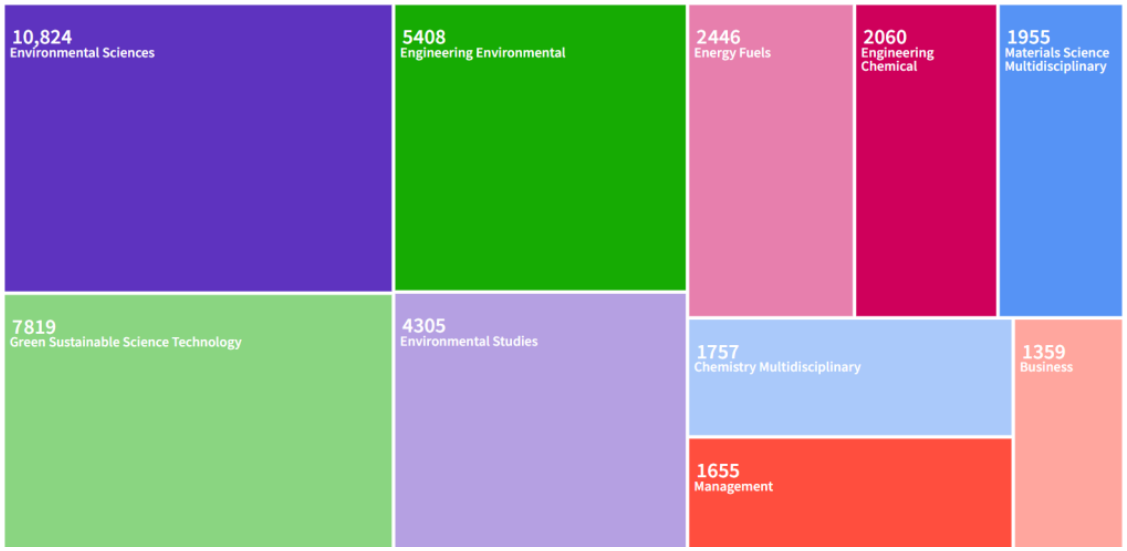


Figure 1. The scientific papers identified in the Web of Science database on the topic of a Circular Economy. Scientific articles (22,487), Review articles (4452), Proceeding papers (2695), Book Chapters (353), Books (17).

The correlation between the publications retrieved by Web of Science database and SDGs, depending on the topic addressed by this paper, is shown in Table 1.

Table 1. The correlation between the publications retrieved by Web of Science database and SDGs, depending on the topic addressed by this paper.

SDG	Circular Economy	Bioeconomy	Circular Bioeconomy
01 No Poverty	21	115	7
02 Zero Hunger	439	348	160
03 Good Health and Well-Being	468	608	197
04 Quality Education	16	13	1
05 Gender Equality	4	31	-
06 Clean Water and Sanitation	1073	464	299
07 Affordable and Clean Energy	753	1376	384
08 Decent Work and Economic Growth	16	23	4
09 Industry Innovation and Infrastructure	272	131	24
10 Reduced Inequality	15	17	-
11 Sustainable Cities and Communities	1070	151	83
12 Responsible Consumption and Production	4928	1329	774
13 Climate Action	1112	851	226
14 Life Below Water	403	118	45
15 Life on Land	135	489	60
16 Peace and Justice Strong Institutions	-	6	-
17 Partnerships for the goals	-	-	-

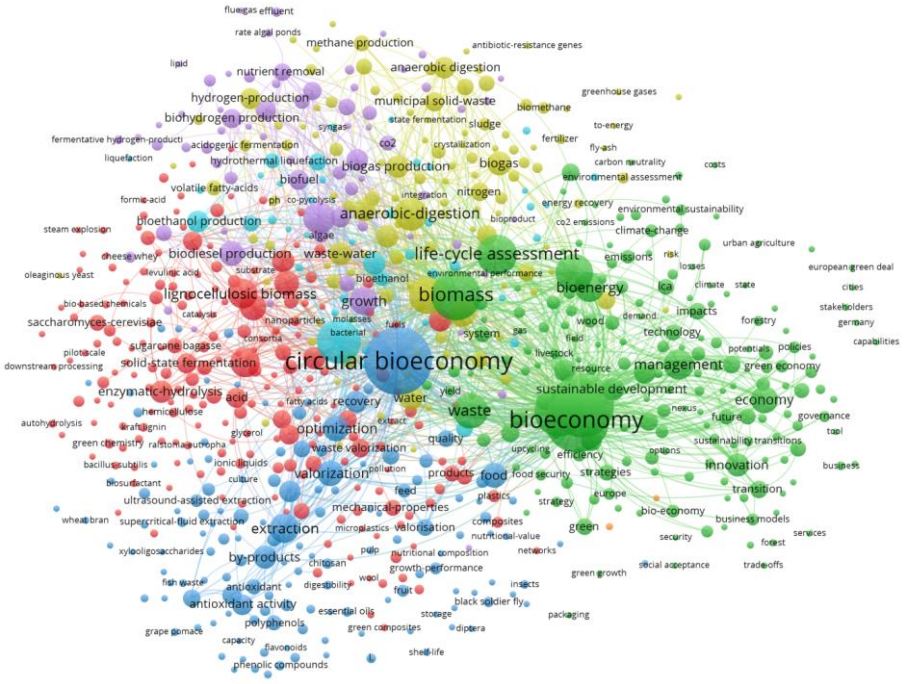
4.1.2. Overview of the Circular Bioeconomy Research and Education and Their Correlation with the Sustainable Development Goals (SDGs)

The "circular bioeconomy" topic network was prepared using the VOSviewer software. The number of scientific papers, review articles, and books published in the period 2015–2025 in different research areas, starting from Environmental Sciences Ecology (742 records) to Transportation (1 record) was retrieved by the Web of Science database as 2054. As can be observed in Figure 2, the topic "circular bioeconomy" is connected with words categorised into five large groups as follows: (1) the blue cluster, corresponding to several outputs, as results of the circular bioeconomy implementation (optimisation, valorisation, recovery, extraction, etc.); (2) the red cluster, corresponding to refinery processes (fermentation, enzymatic hydrolysis, Saccharomyces cerevisiae, etc.); (3) the violet cluster, corresponding to outputs of the circular bioeconomy in terms of energy (biofuel, biogas, bioethanol, biohydrogen production, etc.); (4) the yellow cluster, corresponding to processes that take place to very high temperatures (anaerobic digestion, biochar, nitrogen, carbon, etc.) and (5) the green cluster, corresponding to the main drivers of the circular bioeconomy, defined as strategic variables (European Green Deal, sustainable development, waste management, transition, innovation, etc.).

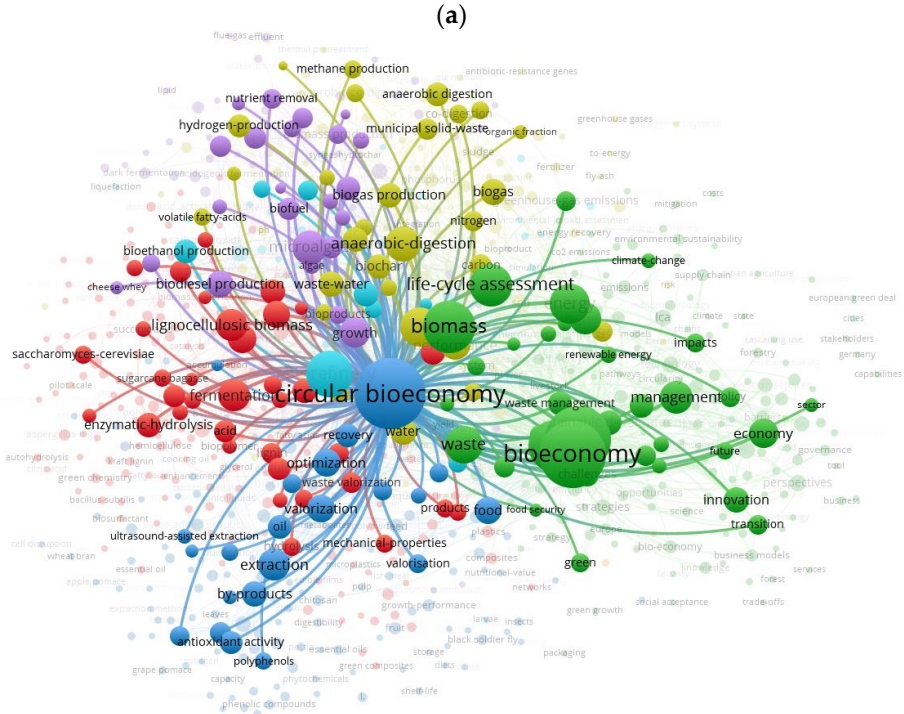
The circles' diameters and the small distances between words illustrate the strong connections between "circular bioeconomy" and "bioeconomy", "sustainable development", "biomass", and "waste", respectively. It can also be observed from the figure below that the keyword "education" is missing.

The documents (articles, review articles, and proceeding papers) identified in the Web of Science database on the topics of the bioeconomy education were correlated both with the SDGs and the years of publication. As can be seen in Figure 3, the highest number of documents (53) was recorded in 2022. This number increased from a total count of 4 in 2014 to 16 in 2017. The number of publications was almost the same in 2023 and 2024 (40 and 42, respectively). The most prominent research areas in which were framed the papers in the period 2012–2025 were Environmental Sciences Ecology (35 documents) and

Science Technology Other topics (35 documents). In Agriculture, Chemistry and Food Science Technology areas were identified a very small number of documents (10, 6, and 5, respectively), despite their strong connections with the fundamentals and applications of bioeconomy. In the area of biodiversity conservation, only two documents related to bioeconomy education were found which was very surprising given the 'bio' connection to the content of both.



(**a**)



(**b**)

Figure 2. Connections between the Circular Bioeconomy topic and related areas. (**a**) Network Visualisation; (**b**) Overlay Visualisation.

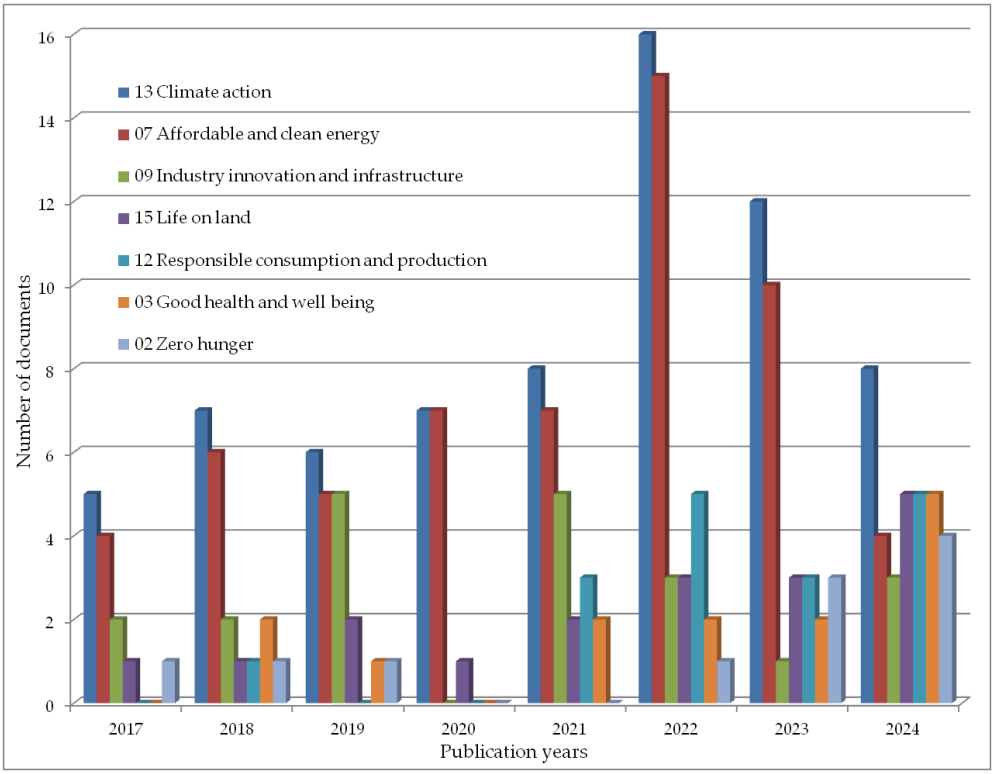


Figure 3. Correlation between Bioeconomy education and SDG alignment in terms of number of published documents recovered from Web of Science database.

If the correlation of bioeconomy education with SDGs is discussed (Figure 3), the content of a total count of 72 documents published between 2012 and 2025 was aligned to SDG 13 Climate Action. Very close to this count, 60 articles were reported as responding to some targets of SDG 07 Affordable and Clean Energy. The SDG 09 Industry Innovation and Infrastructure was reported to be in alignment with the content of 22 papers. SDG 04 Quality Education is not represented in Figure 3, because the total count of documents that scientific content is related to SDG 04 was very small (only one paper/year, in the period 2029–2024). SDG 01 No Poverty and SDG 17 Partnerships for the Goals are mentioned in only three publications each. Two papers, published in 2020 and 2021, respectively, correlate bioeconomy education with SDG 10 Reduced Inequality, while only one document, published in 2021, is aligned to SDG 05 Gender Equality. Both men and women would have opportunities of working within the area of bioeconomy, so raising awareness about gender equality can be emphasised by increasing the number of publications aligned to SDG 05. Incorporating gender into bioeconomy-related education was identified already as one of the four points of action for practitioners in the literature [30].

The scientific papers identified in the Web of Science database on the topics of the circular bioeconomy AND education were correlated both with the Web of Science categories and SDGs. As can be observed in Figure 4, the well represented SDG is SDG 07 (Affordable and Clean Energy), that is missing only in categories Food Science and Technology and Agriculture Multidisciplinary, respectively. This could be considered a gap that needs to be filled imminently, taking into account that both agriculture and food industry are important providers of biomass that can be used for growing renewable energy. Reaching improvements energy efficiency in agriculture and food technologies can contribute to achieving climate targets established through EU initiatives and policies.

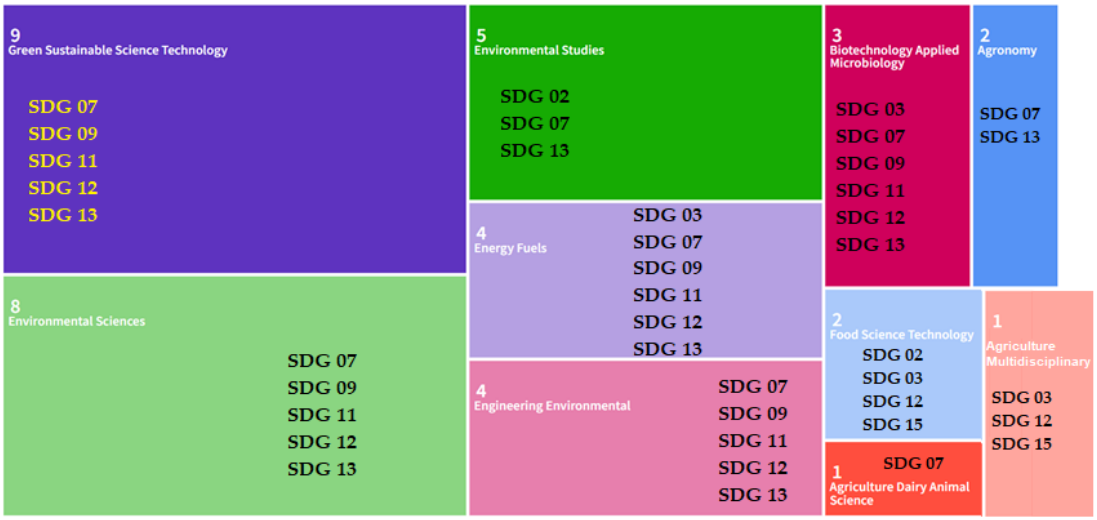


Figure 4. Correlation between Circular Bioeconomy education, WoS categories, and SDG alignment.

4.2. Circular Bioeconomy: An Insight

Becoming an innovative concept in the industry, academia, and policymaking areas too, the circular bioeconomy can be viewed as the synergy of circular economy and bioeconomy agendas [31], although their relationship is rather complex and an ongoing debate [32].

In line with the European Green Deal, by developing circular biobased solutions for closing material cycles, the circular bioeconomy aims to respect our planetary boundaries, addressing, among others, the climate neutrality and environmental performance [20]. However, despite its potential, especially in the domain of biobased products, circular bioeconomy faces challenges and obstacles, such as the lack of a comprehensive and robust framework and an understanding of significant indicators [31]. If work and research such as this is harnessed and shared with mainstream society, it will demonstrate the commitment of many to address climate change and source solutions. The AgroCycle and BioBeo projects have been at the forefront of promoting the circular bioeconomy to industry and also mainstream society. AgroCycle focused on the efficient use of agricultural residues and by-products, developing new technologies and processes to support the transition to a circular agricultural system. BioBeo, on the other hand, has taken a broader approach, focusing on education and community engagement to raise awareness of the circular bioeconomy and its potential applications. Both projects have demonstrated the importance of transdisciplinary collaboration in advancing the circular bioeconomy, as they have brought together experts from a wide range of fields, including agriculture, engineering, economics, and education.

4.2.1. Biomass as Renewable Source

A Naturally Occurring Non-Fossil Organic material [33] is the alternative feedstock to crude oil and natural gas [34] due to its intrinsic chemical energy contained. In the EU, agricultural and forest residues are the main sources of biomass [33]. The term biomass is a generic name for agricultural crops, wood, various plants, aquatic crops (e.g., algae) and weeds, but also for the waste streams formed within the chain from harvesting to consumption and final processing. Residual materials from animal husbandry are also classified as biomass.

In a circular economy, the significance of biomass arises in terms of material products and provision of energy. To create a circular bioeconomy, stakeholders across the value chain—from product design to waste management—need to assess the practical implications of biomass use. A circular bioeconomy requires sustainable biomass as a warrant that

the regeneration cycle is completed. A requirement of the EU renewable energy Directive (Directive (EU) 2018/2001) refers to the sustainability of biomass, which is determined across economic, environmental, and social domains and validated through certification schemes [34].

In the agri-food sector, there are significant opportunities to improve the circularity of the production flow, in the stage of use of goods, but also in the end-of-life stage. Biomass can become a key element in the circular economy, as it is classified as a renewable resource that can capture carbon dioxide from the air and offers a wide range of uses. Carbon dioxide is the start and the end of the biomass lifecycle [34]. Thus, biomass can be constituted as a resource for pharma, food, animal feed, for obtaining various materials, a source of fuel for transport and energy production, etc.

4.2.2. Agri-Food Wastes Biorefinery and Circular Bioeconomy

Seven emerging research areas with potential in the superior utilisation of the agri-food residual streams waste have been identified recently: (1) developing the biochar industry from the circular economy perspective; (2) increasing the role of the biorefinery in recovering valuable biomass fractions within the circular economy; (3) performing LCA studies for the biological waste treatment systems; (4) implementation of the circular economy in the agricultural sector; (5) valorisation of by-products and residues; (6) applications of new biointelligent solutions to ensure circular food and products in a circular bioeconomy; and (7) valorisation of the urban biological waste and food waste through anaerobic digestion.

The potential of materials generated along the agri-food production chain to be used in the circular bioeconomy is high. The aim of implementing circular practices in the agri-food sector is to avoid waste of the biological materials and nutrients and to extract the maximum value from agricultural products by recycling their residues as inputs to new production processes.

The concept of biorefinery, viewed as a pioneering approach in efficient use of resources, is aligned with the principles of sustainability and environmental responsibility [35]. Cutting edge technologies are used in biorefineries with the aim to turn renewable feedstocks into biobased products such as food, feed, chemicals, and fuels [21]. Replacing the fossil fuel sources by biobased substitutes is required for multiple reasons, such as scarcity of fossil fuel reserves, global warming, the costs associated with waste recycling, and the need for energy and products for a growing population.

In brief, the biorefinery concept refers to extraction and functionalisation of the plant constituents with a view to produce food, non-food, and agro-industrial products [21]. Various types of biorefineries are defined based on the individual biomass feedstock, such as corn-based biorefinery, palm-based biorefinery, and algae-based biorefinery, etc. [36]. Another classification of biorefineries takes into account the three categories of feedstock used, as follows: lignocellulosic, algal, and waste [37]. The concept of integrated biorefinery was recently proposed, meaning that multiple feedstocks and various technologies for their conversion are integrated to generate various types of products [36]. Chemical, thermochemical, biochemical, and microbial conversion routes are integrated in biorefineries in search of the best use of biomass [38]. Development of disruptive biorefining technologies, able to sustainable transform the biobased and renewable resources into high-value biobased products will lead to the success of the bioeconomy [32].

A bioeconomy places biorefinery waste at the foundation of the circular economy, considering it a viable mechanism for combating resource scarcity and for mitigation of the effects of climate change, price volatility, and growing product demand. The biofuel production from sustainable biomass feedstock in biomass-based biorefineries provides not only an alternative energy source but also the transition to the circular bioeconomy [39].

The biorefineries, as a strategic mechanism for the implementation of a circular bioeconomy, have infrastructure facilities for the transformation of various biomass feedstocks into several biobased products, such as biofuels, biochemicals, bioenergy, and other bioproducts of high economic value. The biorefineries that use food waste to produce biofuels and biobased materials have been subject to extensive research due to the convergence of policies and regulations towards achieving Sustainable Development Goals (SDGs) under the 2030 Agenda for Sustainable Development.

Food waste biorefineries for production of biofuels and chemicals can significantly reduce the negative environmental impacts and can support sustainable resource management within the circular bioeconomy paradigm [40]. The specific opportunities for an emerging circular bioeconomy are: (i) reducing the environmental footprint and increasing the efficiency of the resources' use; (ii) avoiding the loss of economic value; and (iii) handling the behaviour of the stakeholders.

The bioprocesses carried out in food waste biorefineries, such as fermentation, acidogenesis, and methanogenesis, need to be optimised to generate various biobased products and better transform the linear economy into a circular bioeconomy. The future technological advancements in food waste management are expected to capitalise the multi-functionality of the products, the trade-offs between resources, food waste, and resource allocation in a circular system.

Prior to being discarded, food waste should be categorised into edible (avoidable food waste) and non-edible (unavoidable food waste). Regarding the first category, mitigation measures can be taken to decrease its amount from production to consumption, for unavoidable food waste are required proper waste management and reuse practices and policies [41].

As stated previously, developing a circular bioeconomy is reliant on biorefinery inclusion. This implies various key bioprocesses can be employed for food waste valorisation. A literature review referring to bioproducts obtained by fermentation of food waste, such as bioethanol, biohydrogen (a sustainable green fuel), volatile fatty acids that can be subsequently converted to biobased products (i.e., alcohols, polymers and pharmaceuticals, biofertilisers), biogas and biohytane (a clean fuel with good calorific efficiency) or furfural and hydroxymethylfurfural that can be used for production of different chemicals (including food additives) is presented in Table 2.

Incorporating the principles of the circular bioeconomy into the system for utilisation of food waste led to consolidation of the system, to fully utilise all waste fractions through biorefinery, to promoting sustainability and profitability throughout the food chain [42].

Table 2. Bioproducts obtained through fermentation of food and agricultural waste.

Product	Substrate	Reference
Biocomposite board	Oil palm biomass	[43]
Biodiesel	Food waste and municipal wastewater	[44]
	Waste cooking oil	[45,46]
	Sweet sorghum bagasse	[47]
	Agro-industrial co-products	[48]
	Cheese whey	[49]
	Sugarcane molasses	[50]

Table 2. *Cont.*

Product	Substrate	Reference
Bioethanol	Food waste	[51]
	Agricultural and crop residue (corn-cob, wheat straw, bark of cassava)	[52–55]
	Sugarcane bagasse	[56,57]
	Food residues (individually and blends: potatoes, processed foods, fruits)	[42]
Biohydrogen	Municipal food waste	[58]
	Vegetable waste	[59,60]
	Kitchen wastewater	[61]
	Food waste	[62]
	Date byproduct	[63]
Biohythane	Food waste	[64–66]
	Corncob	[67]
Butiric acid	Wheat straw	[68]
Furfural and hydroxymethylfurfural	Wheat straw Sugarcane bagasse	[69,70]
Lactic acid	Citrus waste; coffee waste	[71,72]
Phenolic compounds	Agro-wastes (coconut coir fibre, pineapple peel, pineapple crown leaves, kenaf bast fibre)	[73]
Polyhydroxyalkanoates	Food waste based acidogenic effluent	[74]
Polyhydroxybutyrate	Rice bran, corn wastes, rice straws	[75,76]
Volatile fatty acids	Food waste	[77–80]

The obstacles regarding the higher utilisation of biowaste lie mainly in technology, underscoring the importance of conducting more research on the following: (i) improving bioenergy production to compete with fossil fuels; (ii) developing governmental support and research and development policies for the use of biological waste and the optimisation of its valorisation process; and (iii) the adoption of advanced technologies to generate products with a competitive advantage and the implementation of some facilities on a commercial scale. In this sense, the role of the Life Cycle Assessment (LCA) methods to increase the sustainability of commercial bioproducts and biofuels is considered of high importance.

Indicators of Sustainability

The development of biorefineries should be aimed at producing value-added bio-products from various renewable resources. Following circular bioeconomy principles, the assessment of the efficiency and sustainability of the processes is strong related to the implementation of the biorefinery concepts in industry [81]. Three pillars for assessment of the sustainability of a biorefinery scenario are described by Ioannidou et al. [81] as follows:

- Techno-economic pillar, with reference to the assessment of process profitability and the costs of environmental impacts (i.e., human health, human welfare, environmental resources and global systems impacts;

- Environmental pillar, with reference to the assessment of the entire or part of the product life cycle. The environmental impacts related to the production of a product are assessed by using LCA, its general framework being specified in ISO 14040:2006 [82];
- Social pillar, with reference to various socioeconomic indicators found in relationship with human well-being, such as health, safety, employment, job satisfaction and social justice issues.

Besides the relevant sustainability indicators, the circularity of the bioeconomy is accomplished by choosing the optimal combination of end-of-life (EoL)/end-of-use (EoU) scenarios. In the case of biobased products, EoL options and efficient waste management are key factors in development of their resource efficient life cycle [81]. Optimal EoL routes should be identified from case to case with a view to turn the biobased products into valuable resources for the circular bioeconomy, generating value by avoiding the landfill [83].

With a special focus on the EoL of biobased products, the circular bioeconomy must consider techniques for better life cycle management. The impact of biobased products on sustainability can be assessed by using the life cycle thinking (LCT) and its tools: LCA (life cycle assessment), LCC (life cycle costing), SLCA (social life cycle assessment), and LCSA (life cycle sustainability assessment) [84]. A key role in EoL management was proved to be held by costs of waste disposal, resource efficiency and EoL responsibility, respectively [83].

4.3. Bridging Industry and Bioeconomy Education

To effectively integrate the work of industry and research into bioeconomy education, a multi-faceted approach is required that aligns educational objectives with industry needs, policy frameworks, and societal goals. The EU's bioeconomy strategy emphasises the importance of education and training as critical enablers for the bioeconomy, underscoring the need for curricula that are responsive to industry dynamics and sustainable practices. Former president of Ireland and member of The Elders Mary Robinson insists: "Education for climate justice must be transformative and interdisciplinary, breaking down silos between fields of study. Only by integrating knowledge from science, economics, law, and social justice, can we equip the next generation with the skills and ethical frameworks to tackle the climate crisis effectively" [85].

This call for interdisciplinary education resonates with the need for teachers to engage in transdisciplinary research when teaching bioeconomy concepts. Through professional development and collaborative networks, educators can integrate diverse fields such as environmental science, economics, and ethics, aligning with Robinson's vision for a holistic, action-oriented educational approach to the climate crisis.

The European Union's bioeconomy strategy also highlights the crucial role of education and training as foundational to advancing the bioeconomy. It emphasises the development of curricula that can adapt to industry trends, address sustainability, and support the transition to a circular bioeconomy. According to the strategy, education systems at multiple levels—higher education, vocational training, and entrepreneurship—must be updated to meet the evolving needs of biobased sectors and sustainable practices. This approach ensures that bioeconomy-related skills are widely disseminated across society, creating an essential link between education and industry that is vital for driving sustainable innovation in Europe [16,86,87].

4.3.1. Transdisciplinary Curriculum Design

The complexity of the bioeconomy requires a transdisciplinary approach that integrates knowledge from, among others, agriculture, oceanography, forestry, pharmaceuticals, food, biotechnology, environmental sciences, economics, political and social sciences, to

name just a few of the core disciplines. The bioeconomy encompasses an entire socio-eco-environmental system with many interdependencies and system dynamics that come together at the interface of bioeconomy solutions.

Academic institutions have a crucial opportunity to design curricula that reflect this transdisciplinary nature, incorporating the voices of youth participants and global citizens through projects like the BioBeo initiative and other funding initiatives. This ensures that the interconnectedness of various fields within the bioeconomy is actualised. According to the EU Bioeconomy Strategy, fostering transdisciplinary skills is essential for developing a workforce capable of addressing the complex challenges posed by the bioeconomy [88]. The BioBeo project [1] exemplifies this by developing educational programmes that blend diverse disciplines with practical applications, enabling participants to gain a holistic understanding of bioeconomy concepts across all levels of education in Europe. The content of these programmes is built on the work of transdisciplinary researchers across the project, which is then conveyed to mainstream society through relational pedagogical approaches.

"Relational pedagogy fosters deep, meaningful learning by emphasising relationships among students, teachers, and content. It allows learners to engage critically with their environment and others, promoting empathy, collaboration, and co-construction of knowledge, which is particularly effective in addressing complex, interdisciplinary issues" [89]. Aspelin's words highlight how relational pedagogy enhances learning by encouraging relationships, interactions, and connection, making it a powerful approach for tackling interdisciplinary and transdisciplinary challenges like the need for greater sustainability and the potential of bioeconomy education.

Transdisciplinary educational approaches, particularly in relation to climate change, have been increasingly recognised as essential for creating solutions to multifaceted global challenges. A key benefit of these approaches is their ability to transcend traditional disciplinary boundaries, facilitating innovative solutions through the integration of diverse perspectives and expertise [90]. This method is particularly valuable in the context of bioeconomy education, where knowledge from a wide array of fields is necessary to tackle environmental, economic, and social issues. According to recent research, transdisciplinary approaches are most effective when they engage stakeholders from various sectors in the co-creation of knowledge, fostering a sense of shared ownership over the solutions developed [91].

Educational researchers have emphasised the importance of incorporating sustainability into curricula through transdisciplinary frameworks that emphasise systems thinking. Wiek, Withycombe, and Redman (2012) highlight how sustainability education benefits from transdisciplinary approaches by teaching students to understand complex problems in a holistic manner and to collaborate across disciplines [92]. Such approaches are particularly important in addressing climate change and presenting bioeconomy solutions, where a confluence of environmental, social, and economic knowledge is required.

4.3.2. Industry–Academic Partnerships

Strengthening collaborations between academic institutions and industry is essential for ensuring that education programmes align with both current and future industry and societal needs. These partnerships facilitate transdisciplinary research to further the sustainable development conversation cohesively. Ecofeminist scholars such as Vandana Shiva highlight the necessity of education that bridges practical applications with theoretical insights, advocating for a pedagogical approach that is relational and holistic. Shiva asserts "we must rethink development to foster symbiotic relationships between nature and human activity, which should also be reflected in educational practices" [93]. The BioBeo project draws heavily on relational pedagogy, integrating educational theory into sympathetic

industry practices, providing a tangible link between theoretical knowledge and real-world application [1].

4.3.3. Policy and Regulatory Frameworks

Incorporating policy and regulatory studies into bioeconomy education is essential for preparing students to navigate the intricate legal, economic, and environmental landscape of a bioeconomy. Plumwood (2002) argues, a critical ecological approach to education must challenge hierarchical structures, a principle that extends to understanding and engaging with regulatory frameworks in the bioeconomy [94]. Plumwood (2002) [94] emphasises that "education should prepare individuals to think relationally and critically about the regulatory environments that influence both human and non-human lives" pointing to the need for a transformative educational approach that not only conveys technical knowledge but also fosters critical engagement with policy systems.

Transdisciplinary researchers play a crucial role in addressing the intricate relationships between societal transformation and the development, implementation, and evaluation of public policies. By collaborating across disciplines and engaging with real-world issues such as climate change, researchers generate evidence-based insights that guide the formulation, implementation and assessment of public policies. When transdisciplinary efforts are prioritised, academics contribute not only to scientific knowledge but also to policy development by producing research that directly informs governmental and regulatory frameworks. Such research highlight how academic institutions can act as bridges between science, society, and policymakers, ensuring that policies are both informed by cutting-edge research and reflective of societal needs [90].

Transdisciplinary research projects such as Horizon 2020 funded AgroCycle and Horizon Europe BioBeo, bring together participants from diverse fields, ranging from environmental science to economics, sociology, biosystems engineering and education, to name but a few. Knowledge is co-created that addresses complex, systemic issues like climate change. This co-creation of knowledge not only generates innovative solutions but also provides robust evidence for policymakers, helping them craft effective, sustainable policies. By embedding this process within academic curricula, universities can cultivate a new generation of students who are not only proficient in technical aspects of the bioeconomy but also equipped to influence and shape policy through informed, evidence-based approaches [92].

In addition to influencing the formulation of public policies, transdisciplinary research plays a significant role in their evaluation and assessment. Through collaborative projects, academics and students can explore the real-world impact of bioeconomy-related policies and contribute to their continuous improvement. This approach aligns with the EU's focus on bioeconomy policies, which emphasise the need for dynamic, flexible regulatory frameworks that adapt to ongoing scientific and societal developments [88]. By integrating policy studies into bioeconomy education, students become better equipped to navigate and influence these regulatory frameworks, ensuring that bioeconomy solutions are both sustainable and just [95].

The policy dimension of transdisciplinary research is particularly important for addressing climate change, as it allows for the incorporation of diverse perspectives and stakeholder interests into the decision-making process. Pohl and Hadorn (2007), note transdisciplinary approaches help bridge the gap between academic knowledge and societal action, offering a structured method for involving policymakers, academics, and citizens in co-developing solutions [91]. This collaboration fosters not only a deeper understanding of the regulatory challenges but also the generation of policy options that are inclusive, equitable, and grounded in evidence.

Universities, therefore, have a pivotal role to play in embedding transdisciplinary research within their curricula and ensuring that future bioeconomy professionals are well-versed in the policy and regulatory dimensions of their field. By integrating policy studies with practical research projects like AgroCycle and BioBeo and others, academic institutions can prepare students to address the complex regulatory challenges of establishing a bioeconomy and to actively contribute to shaping the policies that will govern its future development.

4.3.4. Lifelong Learning and Professional Development

As the bioeconomy evolves, continuous learning and professional development are essential for maintaining awareness of the latest advancements and best practices. Jarvis (2009), while not primarily focused on the climate crisis, has written on the broader ethical dimensions of lifelong learning in the context of global challenges [96].

"As lifelong learning becomes increasingly essential in a world facing environmental degradation, it is imperative that education equips individuals not just with skills for employment, but with the capacity to critically engage with the ecological crises that threaten human survival" [96].

Lifelong learning, particularly for educators, must extend beyond immediate professional competencies. In the context of teaching bioeconomy and sustainability, it should extend beyond skills but also foster a deep understanding of and response to the climate crisis through an awareness of the interconnectedness of all life. This can be strongly nurtured through relational pedagogies in the unpacking of bioeconomy content in schools, educational settings and across society. Through professional development and collaboration, teachers can integrate these broader ethical concerns into bioeconomy curricula, in line with Jarvis's view on lifelong learning as a tool for addressing global challenges.

Todd emphasises that lifelong learning must be relational and inclusive, promoting an education that continually reshapes the individual in response to the world. Todd writes, "Education is not merely preparation for life but an engagement with the world that invites responsibility and action" [97]. Universities and industry participants can play a role in collaborating to offer ongoing education programmes, workshops, and seminars focused on emerging trends and technologies in the bioeconomy. Such collaboration emphasises transdisciplinary approaches to education [95]. This ensures that professionals remain competent and innovative in their fields, fostering a bioeconomy that is both sustainable and equitable, reflecting the ecofeminist concepts of interconnectedness and equity for all.

4.3.5. Utilising Technology and Digital Tools

Leveraging digital tools and technologies enhances bioeconomy education by providing interactive and engaging learning experiences. The inclusion of virtual labs, online platforms, and simulation tools makes bioeconomy education more accessible and ensures students remain at the forefront of scientific and technological advancements. Froebel's theories on learning emphasise the importance of experiential education, arguing that "knowledge acquisition is most profound when learners engage with their environment in a meaningful way" [98]. By utilising technology that simulates real-world challenges, educators can align this with relational and ecological pedagogy. This creates a space for students to apply bioeconomy principles while fostering critical thinking and innovation [99]. The technology created however, must be used and applied appropriately and in sympathy with the planet and her needs. Biesta cautions: "Education should not only be about the transmission of knowledge, but also about empowering individuals to act in the world in a responsible way. This includes fostering an awareness of the interconnectedness

of human actions and the environment, and encouraging positive, collective responses to global challenges like the climate crisis" [100].

Incorporating technology and digital tools into bioeconomy education not only enhances access but also fosters critical thinking and creativity, essential skills for tackling complex global challenges like climate change. Robinson (2006) highlights the importance of creativity in education, stating that "creativity now is as important in education as literacy, and we should treat it with the same status" [101]. By integrating experiential, relational, and ecological pedagogies with advanced technological tools, educators can create learning environments that inspire innovation and critical engagement with sustainability. This approach equips students with both the technical expertise and the creative problem-solving skills necessary to drive transformative change in the bioeconomy.

4.4. Educating Teachers in Bioeconomy

To effectively teach bioeconomy concepts, educators must possess not only up-to-date knowledge and skills, but also a deep understanding of evolving pedagogical approaches that foster transformative thinking. The bioeconomy, a system of using biological resources sustainably but in tandem with positive economic purpose, is inextricably linked to pressing global issues like climate change, environmental degradation, and social justice. Fostering a deeper understanding of these interconnected crises requires teaching methods and relational pedagogies that challenge dominant paradigms and inspire creative, equitable solutions. This is particularly important in the context of climate change, where the urgency for action has never been greater. The concept of climate change is no longer a distant, hypothetical threat. It is a lived reality affecting communities across the globe. As such, the role of educators is not only to impart technical knowledge but also to cultivate critical consciousness and engage students in a form of education that is, as Freire advocates, "emancipatory". Freire's pedagogical model emphasises dialogue, reflection, and praxis, where education becomes a tool for liberation rather than mere transmission of facts. In the context of the bioeconomy, this means fostering a learning environment where students critically engage with the economic, social, and ecological dimensions of sustainable development and are empowered to develop solutions that address the complex challenges posed by climate change [102].

Feminist and ecofeminist perspectives further enrich our understanding of how to teach bioeconomy concepts effectively. Ecofeminists such as Shiva and Plumwood have long argued that the exploitation of nature is closely linked to the oppression of women and marginalised groups. Shiva's work on ecofeminism critiques the capitalist exploitation of both natural resources and female labour, arguing for a shift toward more holistic, sustainable practices that respect both ecological systems and human rights [103]. This aligns closely with the goals of a bioeconomy, which seeks to harness biological resources without depleting or degrading them. The bioeconomy should be framed not merely as an economic opportunity, but also as an opportunity to challenge the exploitative systems that have led to the ecological crises we now face. By integrating Shiva's ecofeminist critiques into bioeconomy education, educators reimagine a more inclusive and socially just approach to sustainability, one that emphasises the interdependence of all living systems and challenges patriarchal and capitalist structures [104].

Plumwood's ecofeminist theory highlights the dangers of dualistic thinking that separates humans from nature, a mindset that has contributed to environmental destruction and social inequality. Plumwood (1993) argues for the need to dismantle the hierarchical dichotomies that position humans as superior to nature, men as superior to women, and the Global North as superior to the Global South [105]. In teaching bioeconomy concepts, educators can draw on Plumwood's critique of dualism to encourage students to think

more holistically about sustainability, understanding that the health of ecosystems is deeply intertwined with the well-being of human societies. This approach fosters a relational view of the world, one that is crucial for addressing the complexities of climate change and developing creative, systemic solutions.

Finally, the insights of hooks on engaged pedagogy offer a valuable framework for teaching bioeconomy concepts in a way that centres the experiences and voices of marginalised communities. Hooks (1994) advocates for an educational approach that is inclusive, participatory, and rooted in the lived experiences of students [106]. In the context of bioeconomy education, this means creating spaces where students can bring their own knowledge, cultural backgrounds, and perspectives to bear on discussions about sustainability and climate change. Engaged pedagogy, as hooks envisioned it, is not about passive absorption of knowledge but active participation in the co-construction of understanding. It aligns with Freire's emphasis on dialogue and action and with ecofeminist calls for inclusivity and justice. By incorporating hooks' principles into bioeconomy education, educators can cultivate a classroom environment that not only imparts technical knowledge but also fosters critical thinking, empathy, and a commitment to social and ecological justice [106].

To teach bioeconomy concepts effectively, educators must embrace pedagogies that are relational, transformative, inclusive, and rooted in critical engagement with the socio-ecological challenges of our time. By drawing on the theories of Freire, Shiva, Plumwood, and hooks [102–106], educators can help students develop the skills and consciousness needed to tackle climate change creatively and equitably.

In a practical sense, this approach can be facilitated through the following:

Professional Development Programmes: Continuous opportunities for teachers to update their knowledge and skills.

Collaborative Networks: Facilitating the exchange of knowledge and best practices among educators, industry professionals, and researchers. An example of this is the growing BEST Network (Bioeconomy Education and Sustainability Teachers Network) [107].

Resource Development: Providing comprehensive teaching materials that support high-quality bioeconomy education and the sharing of appropriate pedagogical approaches.

Industry Partnerships: Enabling teachers to gain practical insights through collaborations with bioeconomy research projects.

5. Discussion

The results are discussed concerning the knowledge acquired and instrumentalised in the frame of the BioBeo project (Section 5.1); Circular Bioeconomy, Education and SDGs (Section 5.2), and integration the agri-industry's needs into bioeconomy education (Section 5.3).

5.1. The BioBeo Journey and Experience: Sustainable Knowledge, Innovation, and Learning

Bioproducts, derived from biomass, represent a key component of the circular bioeconomy, offering sustainable alternatives to fossil-based products. These can include biofuels, bioplastics, biobased chemicals, and biopharmaceuticals. However, the successful implementation of bioproducts in the circular bioeconomy requires overcoming several technical and economic challenges.

One of the key challenges is the processing of biomass into bioproducts, which often requires complex and energy-intensive technologies. The development of cost-effective and scalable production processes is essential to ensure the viability of bioproducts in the marketplace. In addition, there are challenges related to the availability and quality of biomass feedstocks, as well as the need for infrastructure and logistics to support the collection, transport, and processing of biomass.

The AgroCycle project addressed many of these challenges by developing new technologies and processes for the efficient conversion of agricultural residues into bioproducts. For example, the project explored the use of anaerobic digestion and fermentation processes to produce biofuels and biobased chemicals from agricultural waste. However, the successful implementation of these technologies requires continued investment in research and development, as well as the creation of supportive policy frameworks that promote the circular bioeconomy. Building on the success of AgroCycle, the BioBeo project and wider researcher, this paper has focused on raising awareness of the technical challenges and opportunities associated with bioproducts through education and community engagement. By incorporating the principles of the circular bioeconomy into educational curricula, BioBeo aimed to inspire the next generation of innovators and decision-makers to find new ways to overcome the challenges of embedding the concept of a circular bioeconomy in society, and also to view the resources of the earth as the gifts they are in the first place, gifts bestowed on us by Mother Earth. Sustainability cannot exist without humility.

EU funded initiatives have highlighted the importance of sustainable agricultural practices and sustainable ways of living in society in the context of a circular bioeconomy. By promoting the integration of these practices into educational curricula, it raises awareness of the benefits of regenerative agriculture and sustainable living and inspires future generations to adopt sustainable practices. Through hands-on learning experiences, participants are encouraged to explore the connections between soil health, nutrient cycling, agricultural productivity, and the interconnectedness of all living and non-living things in a broader circular bioeconomy

Transdisciplinary research, which underpins education programmes such as the BioBeo project, plays a critical role in overcoming barriers to the implementation of the circular bioeconomy. By integrating knowledge and expertise from diverse fields such as environmental science, economics, sociology, and engineering, transdisciplinary research fosters holistic solutions that address the multifaceted challenges outlined above. For instance, educational initiatives can enhance public awareness, challenging cultural and social resistance to circular economy by promoting sustainable consumption habits and fostering a circular mindset among consumers and producers alike [92]. This research-driven education also encourages government policy coherence and provides a framework for overcoming institutional barriers, as it advocates for regulatory reforms that incentivise sustainable business models and address market distortions [108]. Furthermore, by creating collaborative networks between academia, industry, and policymakers, transdisciplinary approaches facilitate the technological innovations and infrastructure needed to overcome technical barriers, such as advancements in waste management and IT systems for CE progress monitoring [90]. Ultimately, education programmes like BioBeo, informed by transdisciplinary research, play a vital role in dismantling these barriers, fostering cooperation across sectors, and accelerating the global transition towards a circular bioeconomy.

Transdisciplinary research exemplifies a holistic vision for the future of the bioeconomy; wherein social factors are intricately woven into the fabric of innovation. By fostering societal acceptance, promoting equity, and ensuring inclusive participation, the project lays a robust foundation for sustainable transitions. This comprehensive approach enhances the resilience and viability of bioeconomic strategies, ensuring they are economically sound and socially responsible, thereby paving the way for a sustainable future for all stakeholders.

5.2. Circular Bioeconomy and the Sustainable Development Goals (SDGs)

The circular bioeconomy promotes sustainable resource management and economic growth and addresses, based on its interdisciplinarity strategy, critical global challenges, aligning with the United Nations' Sustainable Development Goals [31].

In socio-economic terms, the bioeconomy activities agree with SDGs 01, 02, 03 and 08. In ecological terms, there are connections between the bioeconomy activities and SDGs 06, 13, 14 and 15. The economic targets of the bioeconomy activities are in line with the SDGs 07, 09 and 12 [109].

Correlation of circular bioeconomy education with SDG 09 (Industry, Innovation and Infrastructure) if WoS categories Agriculture, Food Science Technology and Agronomy are discussed is missing (Figure 4). Education, regardless of the field of specialisation it targets, is strongly related to research and development. Worldwide, research and development spending is rising. In the European Union the expenditure on research and development (R&D) and the number of researchers per million inhabitants have increased. The SDG 09 focuses on reducing industrial output and the related carbon dioxide (CO2) emissions, so innovative technologies developed as the result of science-based solutions discovered through research and development, applied to bioeconomy should be made known through education at different levels, especially tertiary.

Scientific papers published in WoS categories such as Agriculture Multidisciplinary, Green Sustainable Science Technology, Environmental Sciences, Energy Fuels, Engineering Environmental, Biotechnology Applied Microbiology or Food Science Technology are aligned to SDG 12 (Responsible consumption and production). This significant alignment to SDG 12 could be explained through the need to achieve the sustainable management and efficient use of natural resources in numerous areas of business, both in recovery from the pandemic and to make enterprises more competitive.

As expected, SDG 13 Climate Action was found to have a relationship with scientific articles published in categories such as Energy Environmental, Energy Fuels and Green Sustainable Science Technology that can refer to energy derived from organic sources, but also in category Biotechnology Applied Microbiology, a field concerned, for example, by biobased products derived from renewable biological feedstocks. Improving education on climate change mitigation is one of the targets of SDG 13 (Target 13.3).

SDG 17 (Partnerships for the goals) is not represented in any of the WoS categories in which the papers focused on circular bioeconomy education were published. The projects based on sustainable development are critically important for key areas such as technology and business. So, ensuring the alignment of education for circular bioeconomy with SDG 17 could promote the sustainable development of entrepreneurship and integration of smart technologies into the bioeconomy, preparing students to work in a complex area of bioeconomy. Consequently, this gap should ideally be filled in the near future, the correlation between circular bioeconomy education and SDG 17 being able to be seen as a catalyst for economic growth.

Interestingly, there are some SDGs missing in the scientific literature searched with terms circular bioeconomy and education, such as SDG 16 Peace and Justice Strong Institutions and the above-mentioned SDG 17 Partnerships for the Goals. Further correlations between circular bioeconomy education and SDGs are reported only in early 2025, targeting SDG 04 Quality Education, SDG 06 Clean Water and Sanitation and SDG 14 Life Below Water, respectively.

In brief, aligning education for circular bioeconomy to the SDGs is a need that calls for action. The integration of SDGs in bioeconomy education requires both scientific knowledge and new educational models.

The BioBeo project has emphasised the connections between the circular bioeconomy and the SDGs in its educational programmes across Europe, encouraging learners to think critically about how their actions can address and contribute to the global sustainability goals. Through hands-on learning experiences and real-world scenarios, bioeconomy education programmes such as this aim to inspire students to act in support of the SDGs and

to consider the role of the circular bioeconomy in creating a more sustainable future. Bozzola and McKinley state: "transdisciplinary projects foster collaboration across various fields of knowledge, enabling holistic approaches to education that are essential for addressing the SDG 4 on quality education. These projects, especially when related to bioeconomy and circularity, can transform mainstream societal understanding by connecting scientific, environmental, and economic disciplines, thus promoting an educational shift towards sustainability through nature-inspired models" [110].

5.3. Integration Societal Needs into Bioeconomy Education

Integration the agri-industry's needs into bioeconomy education in mainstream society refer to general societal aspects regarding consumerism also, drawing on policy, the literature and strategies for bioeconomy. "Alternatives to consumerism must be sought, and one such alternative is the circular bioeconomy concept. This involves systemic change in the economy, environment, and society, reflecting the three pillars of sustainability—economic, social, and environmental" [111].

Developing a bioeconomy supposes an integrative approach between traditional sectors (agri-food, fisheries and aquaculture), industry, science and research, technology, as well as public administration, with particular emphasis on education. Stakeholders' interaction and knowledge transfer can be facilitated by thematic platforms, regional networks, projects, specialised innovation centres, science parks, etc. Rural innovation partnerships, linking existing local action groups, operational groups and regional innovation systems, can contribute to promoting innovation in the most important sub-sectors (agriculture, fisheries, forestry, food, education).

The presence of economists within research consortia exemplifies the truly transdisciplinary approach necessary for comprehensive bioeconomy understanding and education. The bioeconomy, by its very nature, is deeply intertwined with economic principles, as evidenced not only in the term itself, "bioeconomy", but also in the practical mechanisms required to foster its growth. Economists within the BioBeo consortium provided crucial expertise in understanding financial structures and market incentives—vital tenets that underpin the transition from fossil-based industries to more sustainable, biobased alternatives [112].

Within BioBeo's primary education programme, this interconnection is conveyed to children through innovative language-based activities, such as word games that dissect and explore the components of "bioeconomy". By breaking down the word into its constituent parts, "bio", referring to life and biological systems, and "economy", referring to the system of production, distribution, and consumption, students gain a foundational understanding of how economic principles are essential to the sustainable use of biological resources. This educational approach not only helps students grasp the importance of economic policies and incentives but also encourages early engagement with the complexities of bioeconomy, fostering a holistic understanding from a young age, and an understanding that a bioeconomy functions fruitfully but only in sympathy with planetary needs.

"Transdisciplinary research is particularly suited to not only generate scientific knowledge but also to invent real-world solutions and implement innovations" which actively integrate science into society [113].

The bioeconomy is not only an economic and environmental concept but also inherently social, as it aims to transform production and consumption systems in ways that profoundly affect societies. The transition to a bioeconomy involves reshaping industries, employment, and livelihoods, as well as changing the way people interact with natural resources. The social aspect of bioeconomy is driven by the need for inclusive, equitable, and socially sustainable development. This social dimension can be understood

in terms of social justice, participation, and education in reshaping economies, ensuring that marginalised communities are not left behind in the transition to biobased industries.

Therefore, in the evolving landscape of the bioeconomy, EU research initiatives are striving to integrate biological resources into sustainable economic practices. However, for this ambitious movement to truly flourish, it must embrace a transdisciplinary approach, one that goes beyond mere technological advancements to encompass the rich tapestry of social dimensions that underpin societal acceptance and participation. Imagine a community on the brink of transformation, where the potential of biobased products could significantly enhance local livelihoods. The success of a circular bioeconomy hinges on its ability to engage with these communities, fostering awareness and understanding of biobased innovations. Researchers from diverse disciplines, can play a pivotal role, delving into public perceptions to crafting educational content and approaches that resonate deeply with local communities. Through collaborative efforts, trust and enthusiasm around biobased solutions can be built, ensuring community members feel not only informed but also empowered to participate in a just transition.

Culturally tailored education programmes, encouraging adoption in a way that feels authentic and respectful to community identities must be prioritised. This connection creates a vibrant ecosystem of support for biobased innovations. A fundamental aspect of the bioeconomy is the commitment to social equity. The BioBeo project prioritised social equity through educational programmes designed to support community members, enabling them to actively engage in the bioeconomy concept and, consequently, benefit from the innovations it offers. By providing and co-creating educational resources and training, the project fostered a culture and environment in which community members can acquire the necessary skills and knowledge to participate meaningfully in bioeconomic initiatives. The focus on job creation and the promotion of fair labour practices within biobased sectors can significantly bolster public support and commitment to bioeconomic strategies. BioBeo continues to disseminate such information regarding employment ideas for youth, including children and students, thereby fostering early engagement and awareness of career pathways within the bioeconomy through the BioBuzz newsletter, available for free online.

Connection was made with policymakers to design supportive frameworks that emphasise the social dimensions of sustainability. During the BioBeo Blended Intensive Programme which took place at Maynooth University, Ireland in 2024 [114], students engaged in a critical review of the European Youth Ambassadors' Bioeconomy Vision Document 2024. This initiative exemplified the consortium's commitment to a transdisciplinary approach, which facilitates the integration of diverse perspectives. Such collaboration ensures that policy frameworks are not only economically viable but also socially responsive and inclusive.

In summary, there are three important elements to consider with regard to the social dimension to the bioeconomy concept:

Equitable Access and Social Justice: The bioeconomy has the potential to reduce social inequality by promoting sustainable livelihoods, especially in rural areas. By shifting away from fossil-fuel-based industries, the bioeconomy can create new employment opportunities in agriculture, forestry, and biotechnological sectors. This can empower communities that have historically been dependent on unsustainable practices or external economies. However, to achieve this, policymakers need to ensure equitable access to these opportunities, so that the benefits of the bioeconomy are shared broadly across society [115].

Participation and Stakeholder Involvement: The social aspect of the bioeconomy is also tied to the importance of involving diverse stakeholders in the decision-making process. For the bioeconomy to be truly sustainable, it must incorporate the views, needs, and

values of various social groups, including indigenous communities, farmers, businesses, and consumers. These stakeholders help shape the direction of bioeconomic policies, ensuring that the bioeconomy responds to societal challenges and does not exacerbate existing inequalities [116].

Education and Social Innovation: Education plays a crucial role in the bioeconomy, fostering public understanding and acceptance of biobased solutions. The bioeconomy requires new skills and knowledge that align with sustainable development goals, and this is where social innovation comes into play. Educational programmes can support the social dimension of the bioeconomy by preparing individuals to work in new sectors and by encouraging sustainable consumption habits. This aligns with the concept of a "just transition" to a sustainable economy, which emphasises the social and educational reforms needed to support the shift to biobased industries [117].

6. Conclusions: Policy Implications and Future Works

To conclude, through professional development, collaborative networks, and partnerships with industry, educators are equipped with the necessary knowledge and resources to inspire positive environmental action. By fostering an ecological consciousness and promoting relational pedagogical approaches, teachers can help students understand the bioeconomy as part of the solution to the climate crisis and seeing it as a way of life, thus promoting a holistic approach to sustainability education and living. Shiva states "Education must move beyond just facts and figures; it should instil a deep ecological awareness and responsibility in students. The challenge of climate change demands that education become a tool for empowerment, enabling young people to take meaningful, positive action in defence of the planet and future generations" [118].

The BioBeo project, after extensive research in schools across all levels of education, has produced material for teachers, readily available to download, in order to replicate their bioeconomy education programmes on a local level. Work such as this which has emerged from a deeply transdisciplinary consortium is vital for embedding the concept of circularity and bioeconomy in mainstream society through educational engagement, whether that is through families who choose to homeschool their children or whole school communities working through the material. However, it is important to recognise that it is more than downloads, it is more than materials. It is fostering a deep and ethical connection with the planet. It is knowing Mother Earth and her natural rhythms of reciprocal relationships and respecting them. As transdisciplinary researchers, it is essential that we adopt appropriate pedagogical approaches to how we explore the scientific research we are invited to participate in and to use this carefully and ethically with mainstream society, beyond any limits. Todd articulates this: "In the face of environmental degradation and climate change, education must move beyond a narrow, instrumental focus on sustainability. It should engage students in grappling with the ethical dimensions of living on a fragile planet and the profound implications this has for how we relate to each other and the non-human world" [119].

A bioeconomy aims to develop new biotechnologies and bioproducts for the valorisation of bioresources and the sustainable intensification of their production. The circular bioeconomy combining the approaches of a bioeconomy and a circular economy can become sustainable only if it goes beyond simply replacing the fossil resources with renewable bioresources. A sustainable bioeconomy has the potential to meet several Sustainable Development Goals, and the Pillars of Global Citizenship both in economic and ecological terms.

Integrating the work of industry into bioeconomy education requires a holistic approach that includes transdisciplinary and interdisciplinary research and curricula, strong partnerships between industry and academia, policy integration, lifelong learning, and the

use of digital tools. At the level of primary production, working with farmers, learning about biomass production, and including the perspective of conservation initiatives is crucial to ensure that nature is seen as the source of everything in our daily lives, which can only be sustained if we take care to ensure the health of our ecosystems. It should not be forgotten that a bioeconomy has the food system at its core and therefore food is at the forefront of all circular bioeconomy solutions.

By equipping students and educators with the necessary skills and knowledge, we can foster a society capable of driving sustainable bioeconomy advancements, thereby contributing to the achievement of SDGs and promoting global citizenship and planetary stewardship. All of this however, must be supported by appropriate pedagogical approaches, ideally rooted in relational pedagogies. The interconnectedness of all living things must be at the core of all we do as educators in environmentally sustainable development and bioeconomy as one of many proposed solutions.

Todd stresses that "education must be about cultivating ethical responsibility toward the planet, a responsibility that extends beyond individual actions to collective efforts to address the climate crisis. This demands rethinking the very foundations of what and how we teach" [97].

The alignment of transdisciplinary efforts will ensure that the bioeconomy remains a dynamic and sustainable element within the global economy and education conversation. The combined efforts of initiatives like BioBeo, AgroCycle, and innovative educational research highlight the path forward for a synergistic relationship between education and industry now and into the future.

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