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Can Industry Counteract the Ecological Crisis? An Approach for the Development of a New Circular Bioeconomic Model Based on Biocomposite Materials

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Abstract: The ecological crisis we are facing, in addition to depleting non-renewable raw materials, has driven the emergence of biocomposite (BC) materials as a sustainable alternative that can create new opportunities for industrial product design and development. The use of biological resources in economic processes, as the bioeconomic (BE) model proposes, can lead to a transformation from the traditional linear extractive production logic to a new productive paradigm. This paper analyses technical and scientific information on the valorisation of agri-food waste to which innovative and efficient techniques and technologies have been applied, resulting in natural resource use in new products. Our review aims to explore and assess the production, development and industrial exploitation of renewable biological resources as a way to bridge the transition from the linear economic model to a circular bioeconomy (CBE) paradigm shift. For a detailed exploration and assessment of the research problem, this paper presents a comparative study between two paradigmatic projects organised and financed by different R&D programmes of the European Union (EU). We identify the agents and strategies of a potential BC innovation system, and we propose a conceptual model for the creation of an innovative and alternative industrial-scale productive value chain to replace petrochemical-based composite materials with BC and establish a new paradigm of production and consumption.

Keywords: circular bioeconomy; biocomposite materials; agro-industrial waste; sustainable bioeconomic model; EU Framework Programmes

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1. Introduction

The use of certain materials to develop products is characteristic of different eras. These materials and their production processes establish and define economic models and socioeconomic progress. In turn, these models leave traces in the following eras that condition options for progress.

Modern industrial economies, based on the exploitation of non-renewable resources, have become locked into energy systems and production processes based on fossil fuels. This phenomenon, conceptualized in 2000 by Gregory Unruh as "carbon lock-in", characterizes today's linear economic model [1]. The extraction and excessive use of oil produce toxic emissions and increase waste by-product plastic materials [2], causing irreparable damage to our environment and socioeconomic system [3].

According to a report issued by the United Nations Environment Program (2021) [4], we are currently immersed in a triple ecological crisis: climate change, pollution and biodiversity loss. An additional concern is the increasingly pressing problem of progressive depletion of non-renewable raw materials [5]. Therefore, one of today's challenges for countries worldwide is to steer the economy towards sustainable development (SD). This must be carried out at the political, economic and social levels.

For this purpose, the transformation towards more sustainability involves radical changes to the current development paradigm [6], and this change requires stakeholders' collective action through system building initiatives [7].

In this paper, we discuss how the deep ecological crisis we are facing brings into crisis a carbon lock-in economic model that cannot support new processes of expansion [1]. In this context, we recognize the BE as a new economic-political paradigm [8], emerging as a means that can drive a real transformation to medium-term SD [6].

The BE concept appeared in 1979, but only attracted scientific research interest in the early 2000s. However, not until the mid-2000s did the European Commission (EC) introduce BE into the policy discussions [9]. Clearly, this new economic model has become increasingly important: between 1999 and 2018, 1732 scientific documents (Scopus database) were published [9].

According to Adamowicz's [10] approach, the BE model can be understood from di-fferent points of view, which we are interested in exploring in this study. From one perspective, it can be seen as a *new analytical and cognitive economic concept* whose challenge is its integration with the concept of SD. A second aspect refers to BE as *strategically performed smart actions* to extend economic development by finding new uses for established agro-industry and agriculture development processes [10]. A third aspect describes BE as "a broad and dynamic sector of the contemporary economy that *uses biological resources in economic processes*—live organisms, biotechnologies, biomaterials and bioprocesses—to develop new products and services" [10] (p. 2). BE is based on the production and implementation of renewable biomass resources and their transformation into biomaterials, among other things [11].

Our discussion proposes that one possible way to move in a sustainable direction, is to implement innovative and effective techniques and technologies using natural, environmentally friendly resources [10]. For example, and as an object of study for this research, BC materials can lead to more innovative and efficient production methods that consume fewer resources throughout the bio-based value chains in a context where the availability of land and natural resources are limited [12].

This paper focuses on biomass-based BC as a sustainable alternative to petrochemical-based composite materials and as a possible option to solve the problems identified above. BC are composite materials containing natural fibre reinforcement and biopolymers in matrix form; they are 100% biodegradable and have the same physical properties as synthetic composites [13–15]. They represent the *new generation of advanced biomaterials* [16].

The development, processing and application of BC represent a sustainable alternative that can contribute to the urgent transformation from a linear economic model to a circular one [17]. However, despite the great benefits of BC in terms of sustainability and as a solution to the shortage of material resources, there has been little development in systemic initiatives in this sector which are economically sustainable in the long term.

To counteract this lack and as a novel contribution of this research area, we propose a conceptual CBE model based on BC. This schematic model is based on the need to address this situation in a holistic systemic approach to recognize the different components, the macro and micro processes and the relationships required to make sense the overall CBE model, including both science, industry and transfer mechanisms, as well as policy towards the implementation of biomass-based BC.

The innovation we are proposing lies in the way different "links" are related to each other in a system's complexity. To provide comprehensibility and organisation of all system components, modelling can help to define a clearer representation of how different variables are integrated in its conformation [6]. Significantly for us, various studies show modelling in several sectors, such as land, energy, electricity or agriculture, as a tool to support policy making and achieve the transition towards CBE, and these models are also important instruments to understand the complexity of BE [18] (see, for example [18–21]).

The goals of the paper are:

(1) To explore and assess the production, development and industrial exploitation of renewable biological resources to potentially bridge the linear economic model to a circular one.
(2) To identify the key agents and factors that could be involved in the development of a biocomposite system, verifying the variables and determining factors for its successful implementation in the long term.
(3) To demonstrate the feasibility of developing a new paradigm of biocircular manufacturing and consumption by using BC as drivers of an economic paradigm shift.

To meet our objectives, this paper develops a methodology based on a literature review to expand the understanding and implications of BC. We also analyse the Action Plans drawn up by the EU authorities in the CORDIS platform. The Community Research and Development Information Service (CORDIS) is the main source of EU Innovation and Research results. Furthermore, this paper provides bibliographic material issued by specialised international institutions linked to sustainability and the CBE, highlighting specific regulations and the repercussions of their implementation.

We also provide a comparative study between two paradigmatic projects organised and financed through different R&D programmes of the EU: the Bugworkers (BW) and SSUCHY projects.

The structure of the paper is as follows. Section 2 explores the theoretical framework of the CBE as a transformative economic model and provides an approach to modelling it. The characteristics of BC are also studied as potential drivers of this transformation.

In Section 3, the study cases are described according to aspects: the objectives, the consortia created and the industrial verification results.

Section 4 firstly presents an analytical review of both projects to identify the components, strategies and contributions made by the consortium stakeholders and their relationships that constitute a BC innovation system. Secondly, in this section, as our research results, we provide a conceptual model that establishes guidelines for the development of an innovative industrial-scale production chain based on BC.

Finally, Section 5 ends the paper with some conclusions and discussion points, as well as some future lines of action.

2. The Circular Bioeconomy as a New Economic Paradigm

The linear economic model involves the use of non-renewable resources depleted through unsustainable exploitation [2]. This model has become locked-into petrochemical resources, a phenomenon called "carbon lock-in", as a result of combined interactions between technological systems and governance institutions [1].

To understand if this phenomenon could be unlocked through new alternative economics processes, crossing the barriers of path-dependence industrial production [22], we discuss some aspects of the emergence of CBE and the feasibility of its implementation in the long term. We review the literature that addresses why biomaterials are relevant in this new model and we propose BC materials as drivers of CBE.

2.1. Circular Bioeconomy for a Transformative Transition

The need to reduce the use of petrochemical products, mitigate the ecological crisis, expand the possibilities of obtaining renewable raw materials and promote the development of local economies has resulted in CBE becoming one of the strategic priorities of EU public policies [23].

CBE is not just a superposition between the circular economy (CE) and BE concepts, although both aim to enhance the sustainability of production systems, resource efficiency and carbon emission reductions [24]. Although BE arose from the need to move away from fossil resource dependence, CE has the objective of decoupling economic growth from resource consumption [25].

The fundamental differentiating feature of the traditional extractive economy from the BE is the use of biomass as an input in the value chain of a particular product [26] in [10].

This implies a radical change, positioning the BE (Figure 1) as a new economic model to achieve a comprehensive transformation of the economy and society [5]: "a sustainable European bioeconomy is necessary to build a carbon neutral future in line with the Climate objectives of the Paris Agreement" [23] (p. 5).

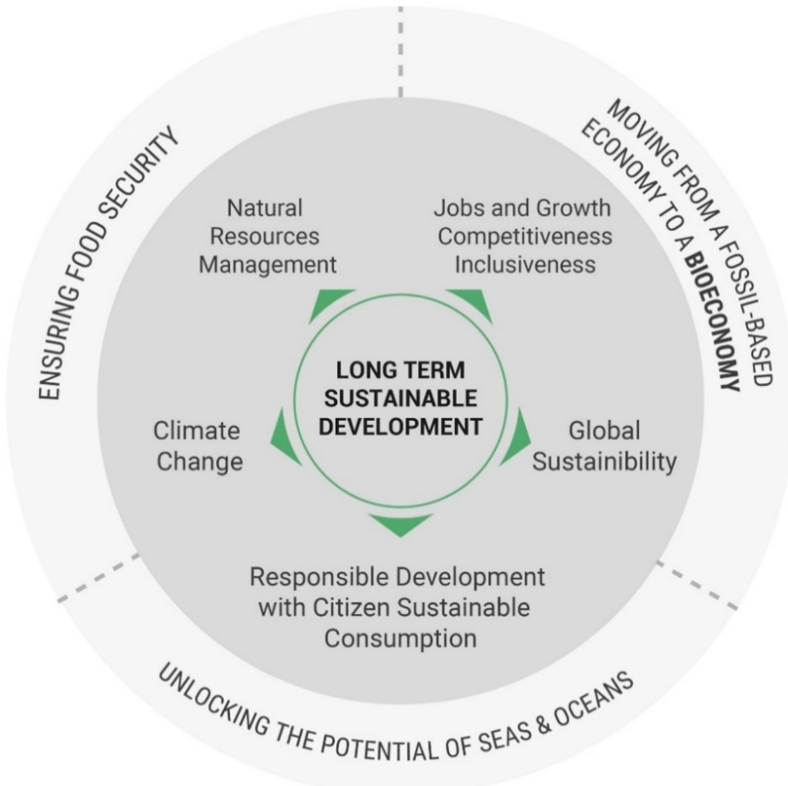

Figure 1. BE as one of three pillars for long term SD. Adapted with permission from Ref. [23]. 2018, European Union.

Linking the core that defines CE to BE, replacing the concept of "end of life" with cyclical productive logic, involves generating a new comprehensive paradigm to achieve SD for the well-being of present and future generations [27].

Under the concept of the CBE, SD is possible, for example, through the revalorization of food waste [11]. The implementation of advanced technologies, such as industrial biotechnology, can lead to the creation of biomaterials derived from the efficient and economical conversion of agricultural waste and by-products—biomass—into highly relevant value-added bioproducts in the short term [28].

In a CBE, unused bio-based food resources should be considered holistically by extracting their maximum ecological, social and economic value and promoting sustainable and global distribution strategies for these resources [12]. It is of the utmost importance to keep in mind that by converting these wastes into value-added products, huge economic and energy losses can be prevented [29].

Currently, the EU produces excessive amounts of agricultural waste, especially in the cereal sector [30]. This points to the feasibility of implementing agricultural biomass as renewable feedstock on an industrial scale. According to the report *Brief on agricultural biomass production* published by the European Commission in 2018, the average agricultural waste in the EU between 2006 and 2015 was 956 million tonnes per year (Mt/y). Of that total, 46% (442 Mt/y) was dry biomass of leaf and stem residues. Agro-industrial waste biomass exceeds economic production [31]. Moreover, inappropriate waste management of these large volumes of solid residues is a serious environmental problem. This is because this waste is often discarded for natural decomposition, adding to the accumulation of solid waste, or it is burnt, emitting toxic gases such as CO_2 and methane that contribute to global warming [32].

Based on these data, it is clear that the large amounts of agricultural waste produced each year should no longer be classified as "waste". They should be considered highly valuable secondary products [33] that can be implemented to develop large-scale biomaterials. To achieve this transformation, industrial biorefineries are needed to develop sustainable bio-based products [30]. A second report titled *Research Brief: Biorefinery distribution in the EU*, also issued by the EC in 2018, notes the scale of biomaterial production, particularly BC. Out of 803 biorefineries identified throughout the European Community that use agricultural by-products as raw materials, 141 produce bio-based composites and fibres [34].

2.2. Theoretical Approach to Modelling the Circular Bioeconomy

The transition from our current linear economy to the use of non-conventional biological resources may be possible throughout the holistic CBE model [35].

Although the CE focuses on the environmental and economic dimensions of sustainability, BE incorporates the social dimension. The CE is interested in the reduction of waste and the reuse of resources with the expectation that commodities will create value by consuming them at the end of their useful life; in BE, waste is reduced and transformed into useful assets by converting waste streams from one process into inputs for another [24]. Therefore, because of this combination, CBE refers to "the reorganization of the business models and the environment with a constructive influence on the employment opportunities" [24] (p. 2).

The transformation process towards the CBE is characterized by substantial complexity, and policymaking needs to consider the design of transition pathways. Modelling is an important tool that can help policymakers deal with uncertainty and better understand CBE complexity [6].

The need to better represent the integration of different variables in a system conformation has motivated model development [18]. Modelling tools describe the entire system components and how they interact with each other [20]. They are an abstract expression, a map to show different components, stakeholders and their relationships and are increa-singly used for testing policy interventions before implementing them [19]. Therefore, modelling can provide essential information to design alternative scenarios, roadmaps or systems to reduce widespread uncertainties [19,21] that might be associated with implementing biomaterials in the transformation processes that BCE requires.

2.3. Biomaterials Driving the Circular Bioeconomy

In 2017, the EC published a new policy strategy titled *Investing in smart, innovative and sustainable industry,* which states that BE and bio-based industry can promote a true transformation towards a new sustainable industrial age [36].

As a potential alternative to assist in promoting this change process, we propose biomaterials as key components in new sustainable industrial practices [37]. We identify the development and application of BC materials, a new generation of high-performance bio-based materials [13,15,16,38], as drivers of change from the old fossil-based economic model to an environmentally sustainable model.

Biocomposite Materials

The first scientific study on BC began in 1989 with the research group coordinated by Dr. Alex Hermann, a composite technology specialist, at the Institute of Structural Mechanics in Braunschweig, Germany. The group proposed that BC be established as true alternatives to fossil-based composite materials [39].

The resistance of plastic composite materials to degradation and their accumulation in the environment have positioned BC as a sustainable option to synthetic composites [37] such as epoxy resin and glass fibre. BC can fully replace them [32,39,40]. These materials are commonly known as eco-friendly composites [41,42] or green composites [43,44] since they are the result of a synergistic combination of bioplastic and natural fibres [43]. Using agro-industrial residues to develop fibres—composite reinforcement—and bioplastic—composite matrix—(Figure 2) with high-productivity processes, is an alternative that is being further refined in the scientific and industrial spheres to utilize agricultural biomass to develop BC materials [32].

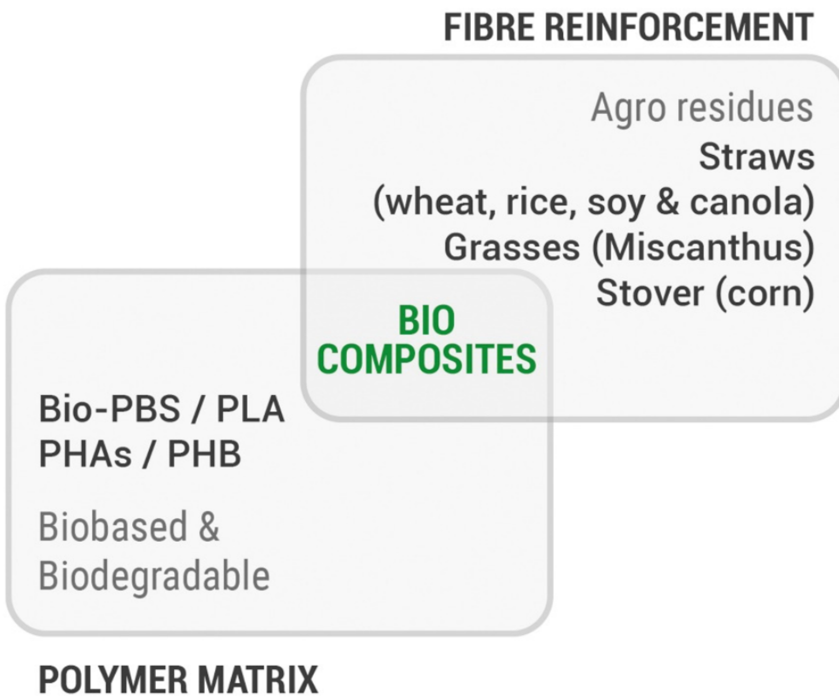

Figure 2. Composition of biodegradable and biobased BC [37]. Own elaboration.

The biopolymer used in producing BC is created through a new biotechnological process called "fermentation technology". This method uses microorganisms and enzymes based on plant biomass in its production [29]. This composition allows BC to degrade naturally [42], facilitating their dematerialization and full integration into the natural cycle without causing any environmental degradation [39].

Among the many benefits that revalorise BC are reduced weight in the final product, less hydrocarbon consumption and fewer emissions. Resistance to corrosion and acoustic and thermal insulation are notable characteristics in the design and development of products [45].

Due to their relevance to this paper, and to expand the BC characterisation and multiple applications, two paradigmatic projects on BC are described in the next section. Then, the comparative case study analysis in Section 4.1 provides us the components to build the proposed model. We study these components to recognise the model's different dimensions and to evaluate the strengths and weaknesses of its development, detecting factors of success for their long-term projection among other variables.

3. Biocomposite Applications and Socio-Environmental and Economic Impact: Case Studies

The EU is aware of the importance of the model change described in the theoretical framework of this article. For this reason, it is pursuing SD by advancing the Paris Agreement on climate change and the 2030 Agenda for SD [36].

By promoting innovation and investment under the "Renewed EU Industrial Policy Strategy", the EC favours the development of a BE model to "accelerate progress towards a circular and low-carbon economy that improves the production of renewable biological resources and their conversion into bioproducts and bioenergy" [36] (p. 12). To achieve this objective, the EC is implementing several Research and Innovation programmes for the development and application of renewable raw materials.

In this comparative case study, select two paradigmatic projects and carry out a detailed exploration and assessment of the background, present status and future scenarios for the implementation of BC in industry.

We first examine the BW project, which is included in the EU's Seventh Framework Programme (FP7) and has revalorised biomass waste by manufacturing BC to be used in experimental prototypes of different product parts [46]. The second case shows an advanced approach to BW, where the main objective is to use biocomposites in highly complex products. The SSUCHY project, developed under the H2020 programme (FP8), shows an evolution in the characteristics of BC and possibilities for their implementation on an industrial scale [47].

Both projects are studied in three aspects: the approach and objectives of each programme, the type of relations established to create the consortium, and the verification process of industrial production. The scientific output resulting from each project is also considered. The information on both cases (data sheets, periodic reports and results) has been obtained from the CORDIS platform and the official websites of some members of the consortia. For the SSUCHY project study, information and documents providing in-depth results have been obtained from its official website [48].

3.1. Bugworkers: New Tailor-Made PHB-Based Nanocomposites for High-Performance Applications Produced from Environmentally Friendly Production Routes

The BW project (2010–2014) was developed under the Specific Programme "Cooperation: Nanoscience, Nanotechnologies, Materials and new Production Technologies" [46] of the FP7 for Research and Technological Development [49], in the research line *New biomass-based composite materials and their processing* [46].

The project's goal was to develop a new cost-competitive and environmentally friendly bionanocomposite material produced by new fermentation culture technology based on combining a biopolymer with different kinds of nanofibers [50]. The new material was produced from non-food agricultural subproducts, particularly wheat straw [40], to produce bioplastic and use the fibres for biocomposite reinforcement.

The BW consortium, made up of 14 partners, was coordinated by the Valencian Technology Centre AIMPLAS. Between July 2010 and June 2014, companies and R&D techno-logy centres, SMEs and large biotechnology and plastics processing companies from Germany, Great Britain, Spain, Portugal, Belgium, the Netherlands, Hungary and Poland worked together. The IST University of Portugal also participated [51].

The industrial partner companies FERMAX, an audio and video door entry system manufacturer from the Valencian Community, and ARCELIK, an electrical appliance manufacturer from Turkey, aimed to implement the research project in their industries.

The final phase of the project involved testing the material's capabilities through the development of industrial prototypes of different product parts. In the case of FERMAX, a microphone support for video door phones was developed [52], and refrigerator and washing machine parts were produced by ARCELIK [53]. More complex prototypes were developed to verify the qualities of the material.

The consortium researchers and two industrial companies declared the project a success. The developed material achieved similar physical and chemical characteristics to those of synthetic composites, and they could be industrialised using traditional plastic processing technologies, such as injection moulding, extrusion and thermoforming, at an affordable cost for biomaterial applications. The BW project was disseminated in seven published scientific papers [46] (see, for example, [40,50]).

3.2. SSUCHY: Sustainable Structural and Multifunctional Biocomposites from Hybrid Natural Fibres and Bio-Based Polymers

The SSUCHY Project (2017–2021) was part of the Bio-based Industries Joint Undertaking Initiative (BBI-JU) [54] research programme under the Specific Programme "Societal challenges: Food security, sustainable agriculture and forestry, marine, maritime and inland water research and the bioeconomy" by Horizon 2020, in the research line *Biopolymers with advanced functionalities for high-performance applications* [47].

The project's objective was to develop renewable resource-based composites, biopolymers and plant fibre reinforcements to produce biodegradable and/or recyclable multifunctional materials. These materials should have advanced functionalities for applications in automotive and aerospace transport and for a high-value acoustic and electronics niche markets.

The SSUCHY consortium was made up of 17 partners working together between September 2017 and August 2021 and was coordinated by the University of Franche-Comté. It included schools and universities, SMEs and large companies, and technology centres from France, Belgium, Sweden, Italy, the United Kingdom, Germany and the Netherlands. The French National Centre for Scientific Research and the non-profit organisation "Bioeconomy For Change" also participated in the consortium [48].

Focused on BBI VC1 (Bio-based Industries value chains 1), that partially involve the conversion of lignocellulosic feedstocks into advanced biomaterials, the project developed specific concepts, technologies and materials to achieve a complete value chain and apply these materials and simulation procedures to the products and prototypes designed [47]. Four industrial partner companies developed different end-user applications to test the advanced functionalities of BC at the demonstrator scale. The French company Trèves and NPSP BV from the Netherlands developed automotive applications. Trèves produced floor and trim sandwich panel structures for cars, and NPSP BV developed a monocoque structure for electric scooters. EADCO (European Aerospace Design Consultants) GmbH & CO. from Germany developed a cockpit panel for a fully electric twin-engine aircraft, and the Wilson Benesch company from the United Kingdom produced a high-performance green loudspeaker system [48].

The SSUCHY project was disseminated in 29 articles and at 5 scientific conferences, among others [48]. Furthermore, the "project partners have invested heavily in human and research capacity for the bioeconomy. In conclusion, SSUCHY has fully aligned itself with European Green Deal objectives by contributing to a greener, circular and bio-based economy" (Ana Ruiz, project manager) [48].

Both case studies show the importance the EU places on R&D in the development of BC materials through specific programmes that call for consortiums to research, develop and apply these materials in industry. Aimed at eliminating the use of non-renewable resources and establishing new productive paradigms, this political decision is reflected in the number of developed and finalised projects published in the CORDIS platform. This commitment is also reflected in the exponential growth of EU funding, the number and diversity of participants in the consortium and the complexity of the results sought and obtained.

It is necessary to establish indicators to assess the benefits of these initiatives based on BC under the dimensions of sustainability (economic, environmental and social) as many drawbacks have been identified [55,56] due to the innovative aspects of BC fields. However, Boland et al. [57] quantified a saving in carbon emissions with the application of e.g., kenaf fibre and cellulose fibre BC of around 10% and 17%, respectively.

4. Biocomposites for a Circular Bioeconomy Paradigm Shift: Scope and Boundaries

4.1. Comparative Variables of the Case Study: Stakeholders, Funding and Projects Result

From the first project developed in the area of BC materials "Biocomposites, sustainnable products", which was carried out within the Fourth FP for Research and Technological Development of the H2020 [5], 46 projects were developed in different specific research lines.

The first one lasted only 5 months (October 1997–April 1998), and just three partner companies took part in the consortium, including two from the Netherlands. The German company Preform Polymerwerwerkstoffe GMBH & CO, a polymer processing company, coordinated the project. The consortium did not receive EU funding [58].

The BW project represents an evolution in several aspects compared with this first project. Although it had some limitations in the experimental process, these shortcomings were further analysed and improved in the SSUCHY project. The purpose of BW was to develop a sustainable alternative to engineering materials that would meet the requirements of different applications in terms of processability, dimensional accuracy and performance [46]. It focused on developing the material, planning potential applications and successfully meeting the goals. However, none of the industrial partners, who developed a series of industrial prototypes, mention the continued use of BC in their products.

The SSUCHY Project surpasses the BW project, especially regarding industrial applications (Figure 3). It was one of the last projects developed within the scope of H2020. It expanded the complexity and capacity of industrial implementation and increased and diversified the contributions made by the consortium partners and the funding (Figure 4) granted by the EU [47].

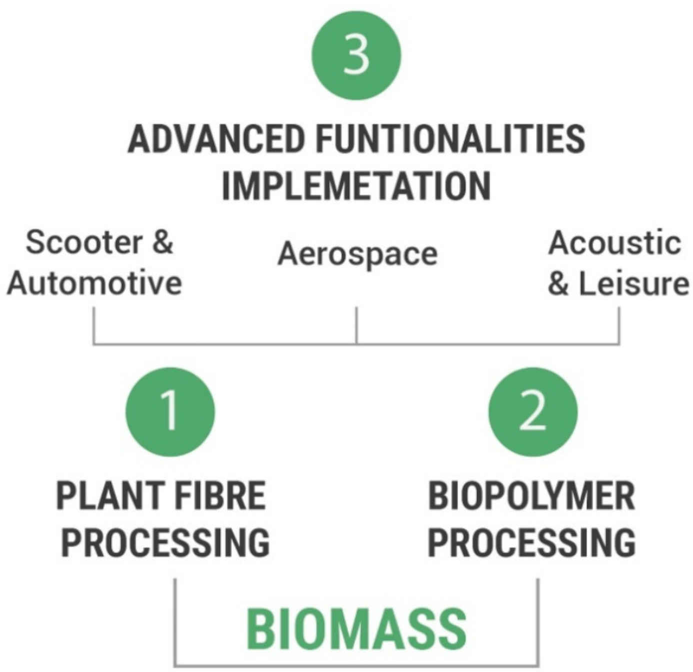

Figure 3. SSUCHY project concept. Adapted with permission from Ref. [48]. 2021, Maxime Robinet.

Concerning general funding, the EU invested EUR 1.9 billion in Research and Innovation in biomaterials and the BE in the FP7, which included the BW project. With its successor, H2020, in which the SSUCHY project was developed as part of the Action Plan "Leading the way to a sustainable and circular economy", the investment was doubled, opening new pathways and solutions for sustainability [23].

The current "HORIZON Europe" programme (2021–2027) [59] anticipates EUR 8.9 billion of investment for research and innovation in "Global Challenges & European Industrial Competitiveness", *Cluster 6: "Food, Bioeconomy, Natural Resources, Agriculture & Environment"*, which makes up 9% of the programme's total and almost triples the budget of its predecessor H2020 [23].

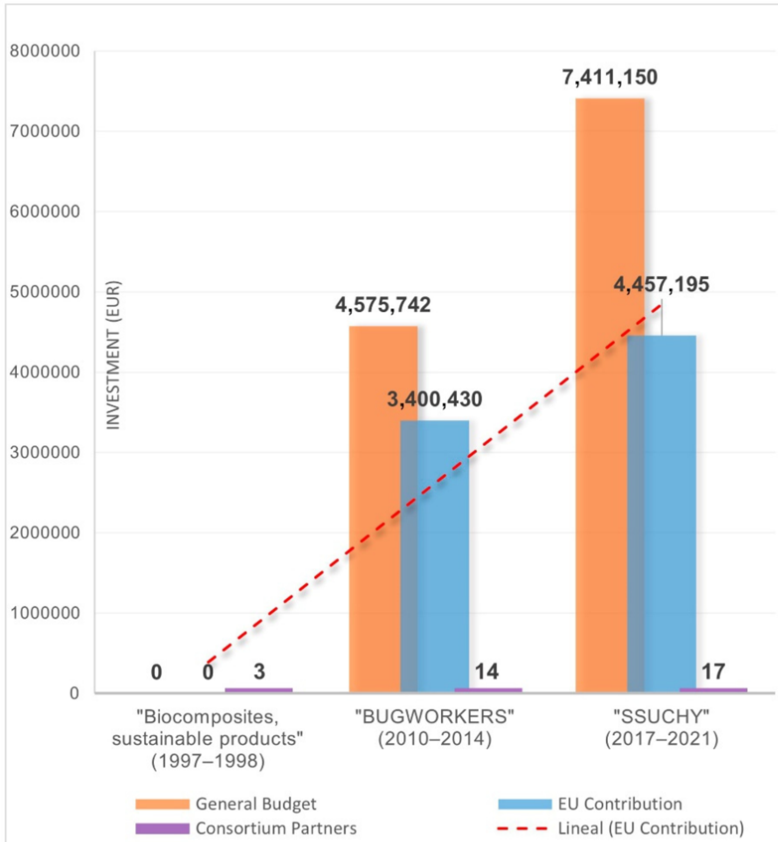

Figure 4. Evolution of the investment (in EUR) made available by the EU and the number of partners involved in each project consortium [46,47,58]. Own elaboration.

Both projects involved the participation of different stakeholders to meet the requirements of the programmes and work together throughout four years to achieve the planned results. Its development and achievement have driven different innovation processes related to, in the BW case, the material development and later, in the SSUCHY project, the material refinement and its industrial application.

From a systemic perspective [60], the consortium's formation allowed the creation of new theoretical and practical knowledge that resulted in innovative sustainable industrial practices with positive socio-environmental and economic impacts. Such a systemic model accelerates innovation processes, and its consolidation promotes long-term implementation.

In Figure 5, we can see how following a public administration programme (EU FP), scientific and technological institutions and industrial companies constitute an BC innovation system, a dynamic and multidirectional system that allows understanding, descry-bing, and influencing innovation processes [60].

Considering the development and results of the case studies analysed, we conclude that the projects' trajectory in approaching the creation of a sustainable value chain are limited.

In Figure 6, we highlight how projects have progressively expanded their scope, but there are stages that still need to be addressed. To counteract this lack and to explain the potential next stages to be included in order to "close the loop", contributing towards a CBE paradigm, in the following section we propose an approach to a conceptual model as a novel contribution of this research work.

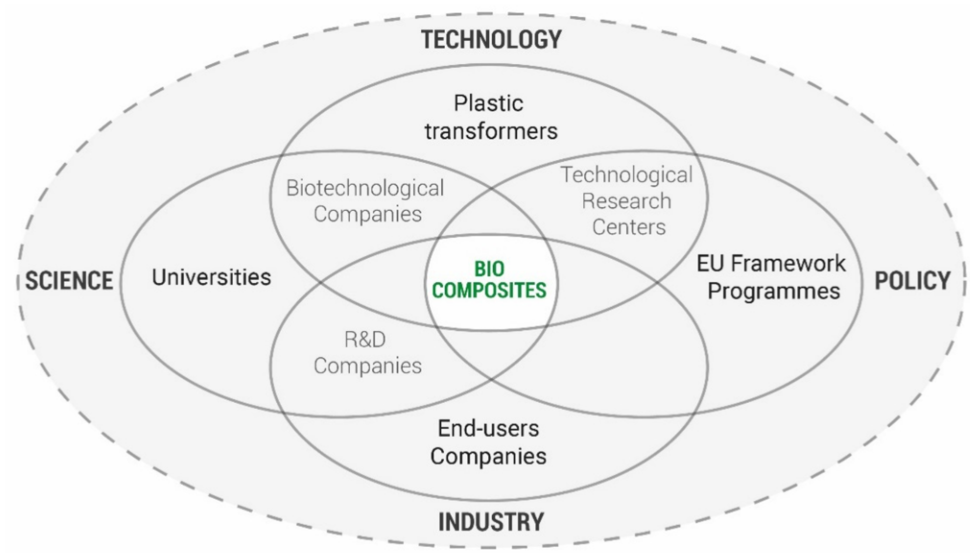

Figure 5. System comprising the BW and SSUCHY project [46,47]. Own elaboration.

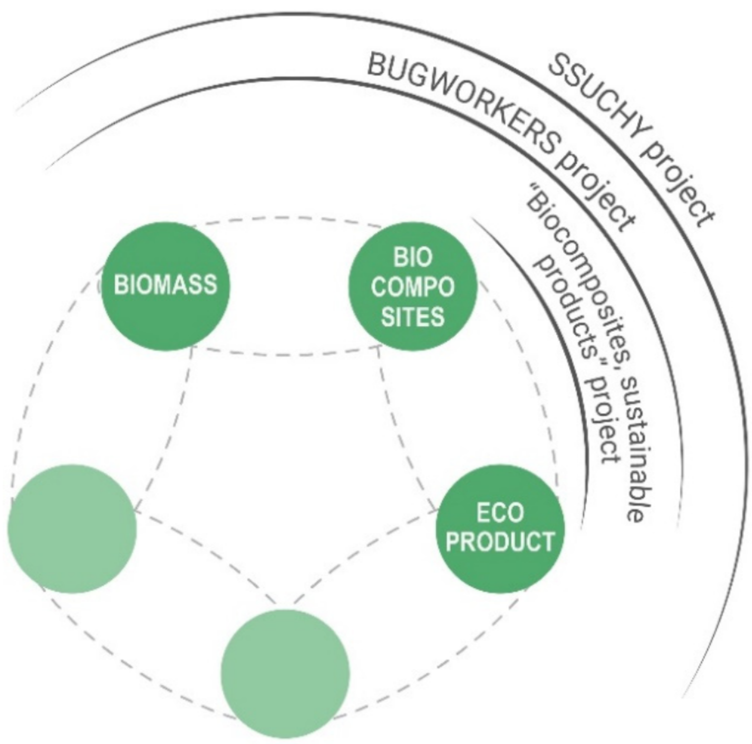

Figure 6. Comparative scope levels in the value chain of case studies [46,47,58]. Own elaboration.

4.2. A Circular Bioeconomy Model for an Innovative Value Chain Based on Biocomposites: An Approach

In line with the bibliographic review and particularly the case studies, we highlight that the complex process needed to drive the transition from a linear economic model to a CBE paradigm shift requires a systemic model to organise and link different components, processes and particular stakeholders towards a common goal.

Placing the BC at the core, we propose an approach to the development of an industrial-scale model to demonstrate that BC are a resource that can truly contribute to the transition to a new sustainable production logic.

To address the question of *whether creating a BC sector on an industrial scale is possible*, we design this schematic model based on CBE principles [23]. This holistic model of a sustainable economy based on BC, is supported by the technical and empirical feasibility of the industrial processes that constitute it. Every stage of the value chain needed to achieve a total positive social, environmental and economic impact are considered.

The conceptual model intends to be a map that can help better understand the proposed BC system's complexity [6] and provide a clearer representation of how the different variables are integrated in its conformation [18]. The innovation of this model lies in how different "links" relate to each other throughout the five stages (Figure 7).

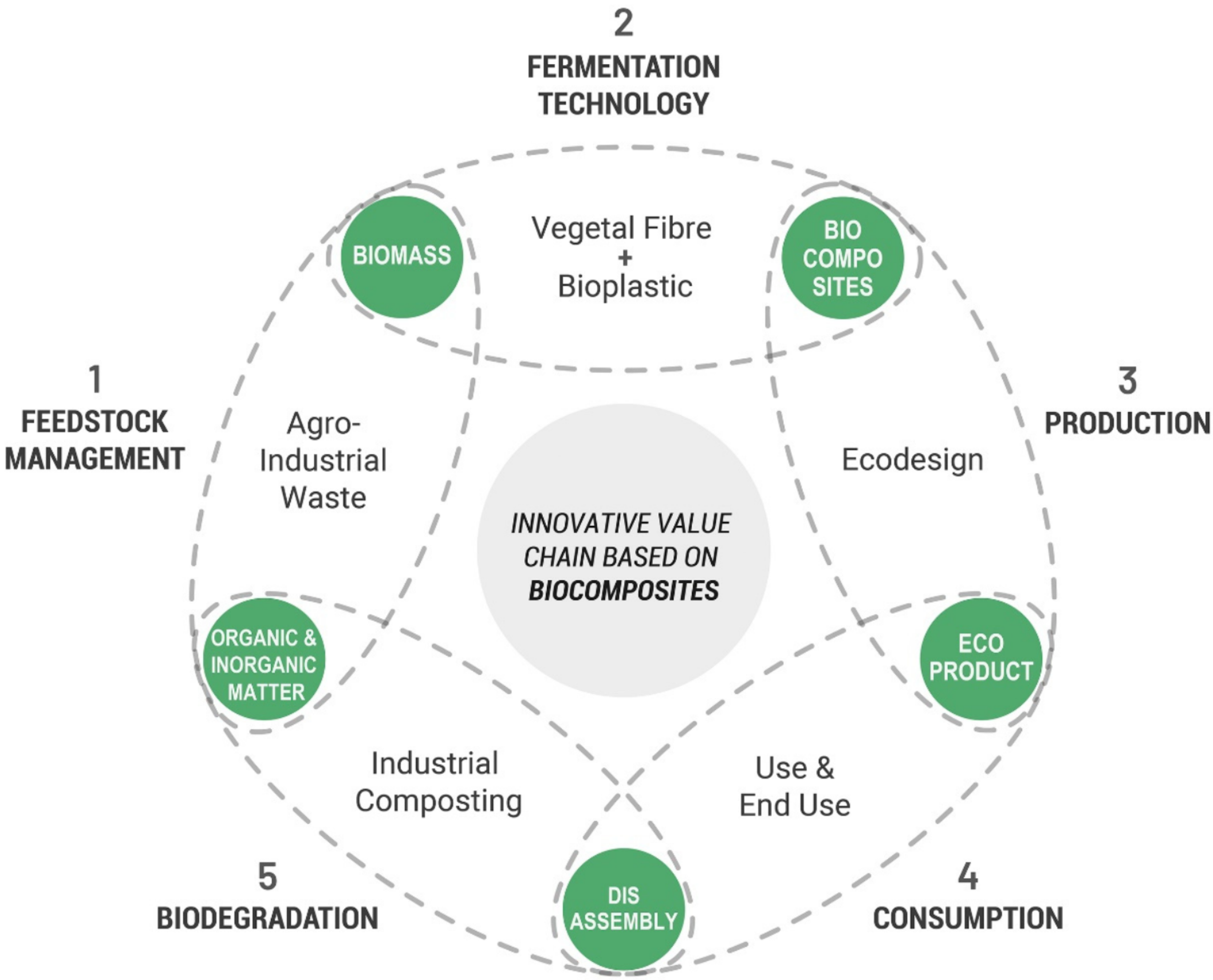

Figure 7. BC-based CBE conceptual model. Own elaboration.

At the macro level in an increasing relationship, from stage one to five, global processes of the BC value chain are defined. Within every link, between each point of intersection, the components and actions under development are placed. At a micro level, individual nodes reciprocally represent both inputs and outputs that feed back to every stage of the process.

Stages 1 and 2 shows how biomass from the primary agro-industrial sector can be transformed into a by-product that contributes to the development of BC based on plant fibres and bioplastics through the contribution of industrial biorefineries (see Section 2.3).

In stage 3, the design and development from sustainable perspectives must consider all the material's dimensions, from its characteristics and properties to its disintegration process.

Stage 4 proposes designing and manufacturing products according to the "disassembly" logic that successfully enables the biodegradation process. In this model, consumers become aware of a product's sustainable qualities, as companies will be able to obtain different certifications displayed on "eco-labels".

Products will have an "expiration date" that allows companies to recover unused products and put them "back into the cycle" through reverse logistic processes.

Finally, in stage 5, cost-effective composting on an industrial scale is a crucial component facilitating the closure loop of the production chain. This enables the transformation of the old model from the "take-make-discard" logic to a new "recuperate-make-degrade" model, resulting in a more efficient and sustainable process than recycling.

The BC-CBE conceptual model provides a particular order of relationships, creating an innovative and alternative value chain to replace petrochemical-based composite materials with BC. The model offers some guidelines to develop an industrial-scale BC sector and establish a new production and consumption paradigm.

5. Discussion and Conclusions

Throughout this paper, we have reflected on the environmental damage caused by industries involved in the non-renewable resource extraction system. One question that has guided this research is *whether industry itself can counteract the ecological crisis* by transforming the traditional production logic.

We realised how substituting fossil resources for renewable biological resources could contribute to creating a new, alternative CBE model based on BC materials using biomass from agro-industrial processes.

Although commonly underrated, biomass is one of the few currently available options to substitute fossil feedstock. It offers an alternative solution with minimal environmental impact to the problem of non-renewable resource depletion [11]. Biomass is at the beginning of the value chain and establishes more efficient and less polluting production, distribution and consumption processes in the following stages.

Biomaterials, in general, and BC in particular, have provided an incentive for industry at the international level. In recent decades, advances in R&D through EU programmes have improved the productive properties of these materials and significantly reduced their final cost. These aspects were among the barriers to the initial implementation of BC. In the cases analysed here, the BW and SSUCHY projects, we have seen that these barriers have already been overcome.

As discussed in the theoretical framework of this paper, the CBE relies on the efficient use of renewable resources. Therefore, implementing BC materials as value chain inputs will boost the bioeconomic model, "driving the EU towards renewing industries, mo-dernising primary production systems, protecting the environment and improving biodiversity" [23] (p. 4).

This document reviews the technical and scientific information on agri-food waste valorisation for the development of BC, which creates new opportunities for product design and development. The production and consumption of these products have significantly reduced socio-environmental impacts compared with those derived from non-renewable resources. BC materials have the potential to become a new paradigm for sustainable advanced materials, promoting the emergence of a new industrial age.

From this research, it is clear that an interest in biomaterials is present in the industrial sectors that can apply them to their industrial processes. The EU has significantly supported and is currently supporting the creation of a pool of interested agents to bring about the birth of a new economic model, as illustrated in our proposal. However, even with EU support, we must not forget that creating a systemic model is always the prero-gative of the actors that comprise it. Incentives through project financing are a sound basis, but progressive adaptation and, above all, consolidation over time is something that only the agents involved can achieve if they decide to pursue this direction. Providing appropriate incentives to these agents at each stage and achieving a common view of the possibilities and benefits of a shift in the economic paradigm can bring about the desired change.

As future research lines, congruent with the aim of mobilising agents towards a change in the production model, we highlight the following areas. The potential formation of the Regional BC Innovation System in the Valencian Community should be studied to evaluate to what extent industry commits to implementing sustainable materials and incorporating them into their value chains in the long term. Another area to be considered is how public policy intervention can support the transition through different strategies to encourage the inclusion of biomaterials in the production chain and discourage the use of petrochemical materials.

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