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Systematic Review

Exploring Supply-Side Barriers for Commercialization of New Biopolymer Production Technologies: A Systematic Review

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Abstract: The development of new biopolymer production technologies is becoming increasingly relevant for tackling the negative impact of linear plastics. Despite these potential benefits, their production and commercialization still face several obstacles that might hinder their widespread adoption. The present systematic review aimed to offer a thorough analysis of the multi-level supply-side barriers across researchers, policymakers, and industry professionals. Searches were performed in Web of Science, SCOPUS, PubMed, and IEEE Xplore between June and July 2023. Publications between 2019 and 2023 were considered for analysis (n = 176). Content was coded following a PICO structure and the results were reported following the PRISMA checklist. We found that technological and knowledge barriers were the most identified, followed by economic, regulatory, supply stability, and behavioral challenges. Moreover, we found that 82% of the documents identified more than one barrier, reflecting the complex interaction between the different challenges in the field. Fostering interdisciplinary collaboration, establishing clear regulatory frameworks, and enhancing communication strategies are relevant recommendations for overcoming these barriers. These findings draft a multifaceted roadmap of the key barriers in the commercialization of new, sustainable biopolymer production technologies, and carry significant implications for future research, policy development, and industry practices.

Keywords: biopolymer production technologies; supply chain; multi-level barriers

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Academic Editor: Maria L. Auad

Received: 10 December 2024
Revised: 14 January 2025
Accepted: 17 January 2025
Published: 21 January 2025

Citation: Possidónio, C.; Farias, A.R.; Domingos, S.; Cruz, B.; Luís, S.; Loureiro, A. Exploring Supply-Side Barriers for Commercialization of New Biopolymer Production Technologies: A Systematic Review. *Sustainability* **2025**, *17*, 820. https://doi.org/10.3390/su17030820

1. Introduction

In the face of escalating environmental concerns, the imperative to reduce the detrimental impact of linear plastics on ecosystems and human health has prompted the quest for more sustainable materials and solutions [1–3]. New biopolymer production technologies have emerged as promising alternatives to traditional petroleum-based polymers and have gained traction as a significant solution to tackle the challenge of linear plastics [4–6].

Biopolymers are natural polymers produced by the cells of living organisms [7,8]. These organic molecules can be produced by different biological sources, which include the following: (1) plants—starch, lignin, pectin, cellulose, alginate, carrageenan, wheat, soy, zein, and natural rubber; (2) animals—collagen, gelatin, silk, chitosan, and hyaluronic acid; (3) algae—alginate, agar, and carrageenan; and (4) microorganisms—polyhydroxyalkanoates (PHA), chitosan, bacterial cellulose, glucan, xanthan, and pullulan [9,10]. Biopolymers can also refer to molecules synthesized through chemical processes, yet originating from biological starting sources such as sugars, amino acids, oils, or natural fats, including polylactic acid (PLA), polycaprolactone (PCL), and polyvinyl alcohol, (PVA; [10,11]. Their increased potential for biocompatibility, biodegradability, and a reduced carbon footprint offers a compelling incentive to shift away from conventional plastics [8,12,13], while promoting a transition towards a circular economy [14].

Furthermore, the number of applications of biopolymers is countless. Many of these applications can be found in the medical industry, including scaffolds for tissue engineering, wound healing, and drug delivery systems [15,16]. Other applications include the food and packaging industry [17,18]; agricultural sector [19,20]; textile and fashion industry [21,22]; technology and manufacturing [23,24]; construction and engineering field [25,26]; and energy and environment industries [27,28].

Despite these advantages and multiple applications, the journey toward widespread biopolymer adoption remains troubled by several obstacles [29–32]. In the context of technical and regulatory realms, addressing challenges related to knowledge gaps is a common hurdle faced by organizations across various industries [33–36]. These gaps can hamper progress and innovation and hinder the market entry of new technologies [37–39]. Furthermore, economic and social aspects might also interfere in the commercialization of new biopolymer technologies, such as lack of funding [38,40] and resistance to change [41,42]. Therefore, it becomes crucial to adopt a multifaceted approach to identify the key barriers among supply chain actors, advance scientific knowledge, and develop best practices to overcome them.

Biopolymers are fundamental in mitigating environmental pollution and ecological degradation. Therefore, it is necessary to outline a systematic gathering of information regarding the main existent barriers in the literature and identify specific areas of concern to effectively tackle these challenges. To the best of our knowledge, the existing data regarding the barriers faced by this sector are scattered and fragmented. Few studies offer a comprehensive analysis of the key challenges hindering the commercialization of new biopolymer production technologies. Therefore, the present systematic review aims to compile the existent knowledge in this regard, examining the intricate landscape of biopolymer commercialization. It explores the complex landscape and the multi-level challenges that might hinder widespread adoption among supply chain actors, including researchers, policymakers, manufacturers, and industry professionals.

2. Method

The protocol used for the present systematic review was registered at INPLASY and can be found here: https://doi.org/10.37766/inplasy2023.5.0076 (accessed on 10 December 2024). Firstly, we conducted a preliminary literature search on Google Scholar, Scopus, and by consulting team members, with the goal of creating a benchmark list of studies that could provide an initial overview of the existing literature, as well as an initial identification of relevant keywords to inform the search string design. This initial step also served to ensure that all the articles in the benchmark list would emerge through our search string. The search string was then developed considering the PICO framework, namely: (1) population—supply chain actors participating in the production, development, and commercialization of biopolymer production technologies, including industry professionals, researchers, and policymakers; (2) intervention—studies encompassing the identification of barriers related to the commercialization of novel biopolymer production technologies; (3) comparator—not applicable; and (4) outcome—qualitative and quantitative results and insights on the multiple challenges of the commercialization of new biopolymer production technologies, from the supply side. The search string was executed in four electronic databases, namely Web of Science, SCOPUS, PubMed, and IEEE Xplore, between June and July 2023. The search strings used for each database can be found in Supplementary Materials.

To capture the evolution of research on this topic over an extended period, we conducted an initial search for the relevant literature published between 2010 and 2023. After extracting the documents (n = 3546) and removing the duplicates (n = 919), we found 2627 documents.

Subsequently, a set of inclusion criteria was defined, regarding language, year of publication, and type of document. This inclusion criteria also served to filter the large number of documents identified. The literature search was limited to papers in the English language, and only publications between 2019 and 2023 were considered. This cutoff point for the selection criteria was determined by the introduction of the European Green Deal, a package of policy initiatives aimed to set the EU on the path towards a green transition, first presented on 11 December 2019.

Furthermore, the inclusion criteria were limited to articles, reviews, and proceedings papers, ensuring the incorporation of high-quality, peer-reviewed sources that directly enrich the field's body of knowledge. Articles and reviews granted access to original research studies, primary data, and analyses, while also presenting a comprehensive synthesis of existing research, facilitating a broader comprehension of the current knowledge status on the topic. Proceedings papers were also included, allowing for early access to emerging research, exploring current trends, and capturing cutting-edge developments in the field.

Focusing on titles and abstracts, we developed screening criteria based on the PICO elements. Three independent reviewers tested these criteria on 10% of the articles from the database, achieving a Cohen's kappa score of 0.66 for interrater agreement. Post training, 207 of the remaining articles were retained after title and abstract screening.

For the selected articles, three team members conducted a full-text screening and critical appraisal. Both internal (methodological rigor and reported data) and external validity (country, business area, identification, and categorization of supply side barriers for biopolymer commercialization) were analyzed. The appraisal criteria were first refined using a random 10% subset. After discussions to address inconsistencies, two raters appraised the remaining studies, resulting in 176 documents being included in the final review.

3. Results

We employed a PRISMA flowchart to illustrate the flow of information across the several stages of the systematic review. We delineated the quantities of identified, included, and excluded records, along with the rationales for exclusions. From the documents included in the present systematic review (n = 176), 118 were reviews, 57 were articles, and 1 was a proceedings paper (Figure 1).

Notably, after 2019, the year of the introduction of the European Green Deal, our analysis of the distribution of published articles revealed a significant increase in publications (Figure 2). From the documents included in the present literature review, we start with 17 from 2019 and end with 59 from 2022. Up to July 2023, we gathered 25 documents.

Additionally, we visually represented the countries featured in the systematic literature review in Figure 3. This graphical depiction aids in comprehending the global distribution of the studies, offering a clearer perspective on research trends worldwide.

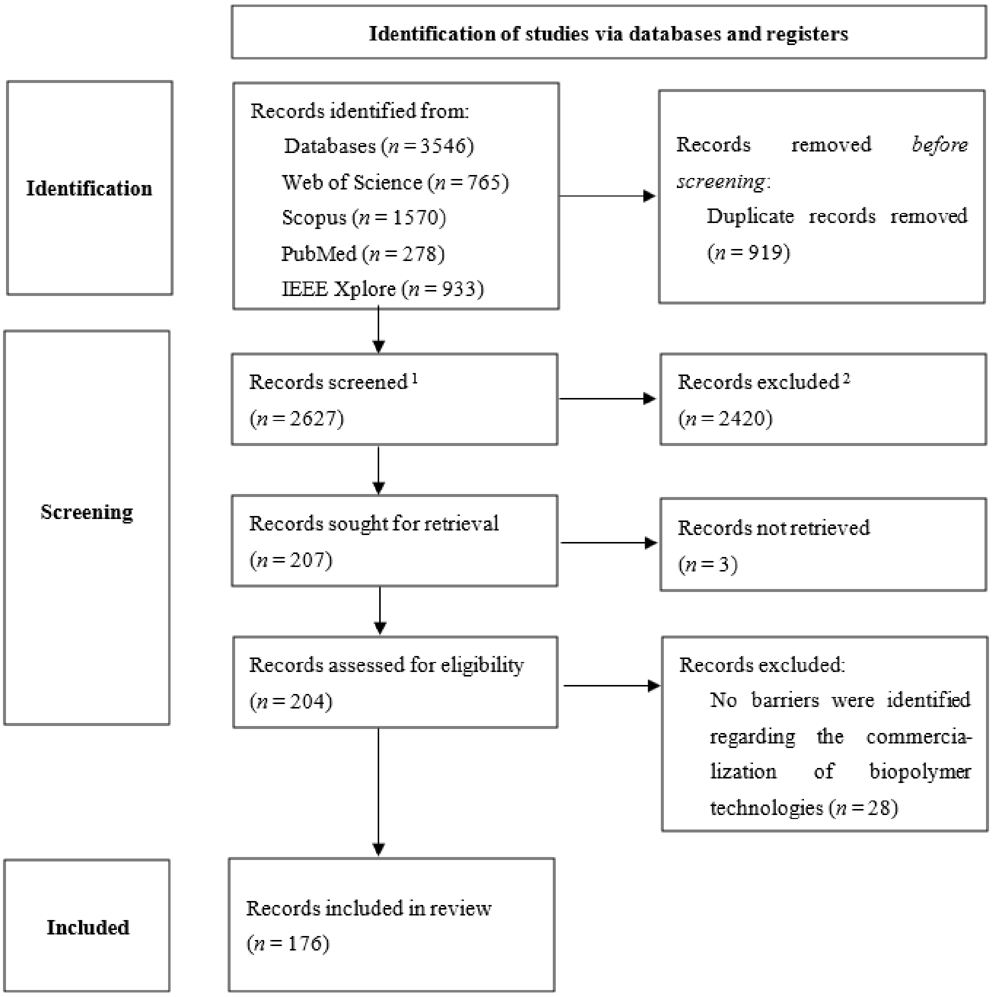

Figure 1. PRISMA flow diagram. Note. [1] Reports were screened at title and abstract level. [2] Type of document, year of publication, and language were defined as exclusion criteria.

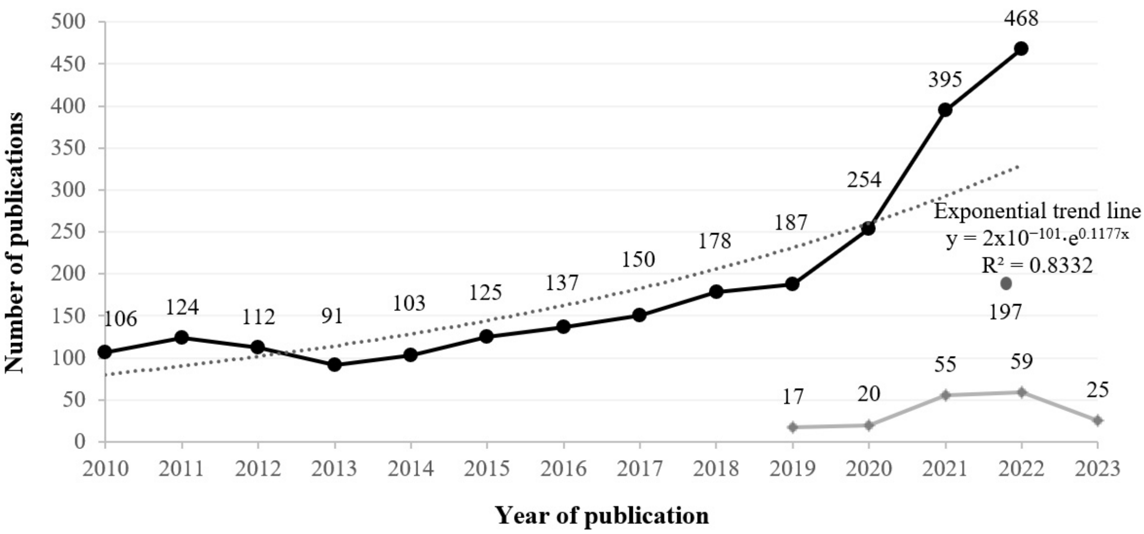

Figure 2. Distribution of articles over the years from 2010 to 2023. Note. ⧫ Publications considered for the present systematic literature review, retrieved from 2019 to 2023. • Publications retrieved from 2010 to 2023 July. Since the documents were retrieved without the year 2023 having concluded, we did not include the number of publications from 2023 (n = 197) in the exponential trend line, since it does not reflect the total publications from the entire year.

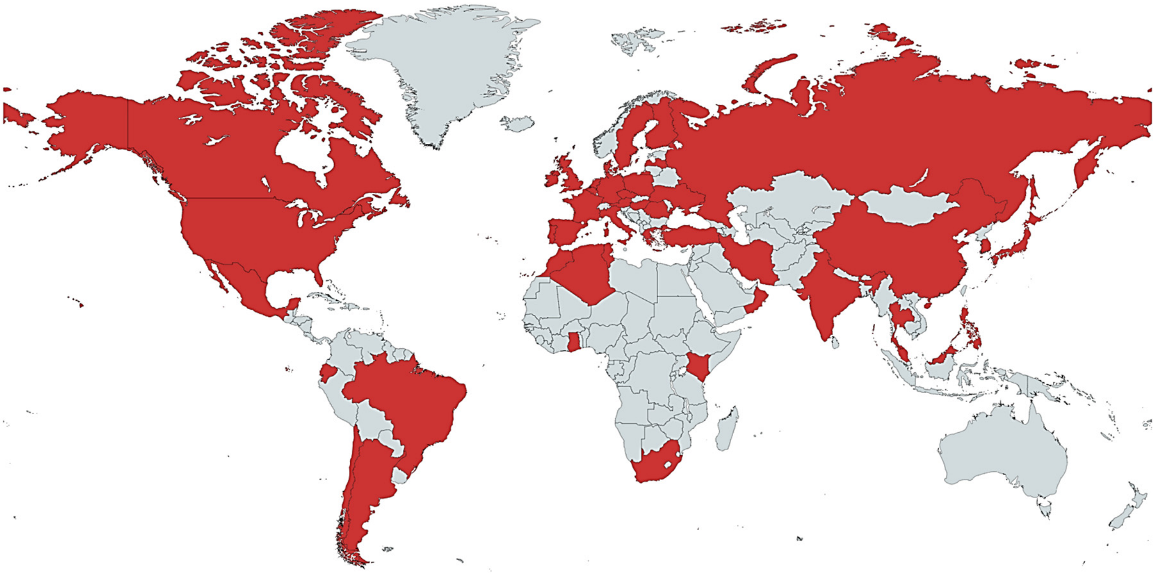

Figure 3. Countries in red represented in the systematic literature review. Note. Forty-four countries were represented in the included studies. Countries represented in more than one study included China (n = 19), India (n = 17), Brazil (n = 12), United Kingdom (n = 11), United States (n = 11), Spain (n = 8), Portugal (n = 8), Germany (n = 7), Italy (n = 7), Canada (n = 7), Malaysia (n = 6), Poland (n = 5), Netherlands (n = 5), Iran (n = 5), Russia (n = 4), Mexico (n = 3), France, Denmark, Sweden, Finland, Greece, Hungary, Turkey, Romania, Serbia, Argentina, Chile, Kenya, and South Korea (n = 2). The following countries documented one study: Ireland, Czech Republic, Ukraine, Latvia, Ghana, and Oman.

3.1. Biopolymer Technologies and Areas of Application

Across the documents, we found different biopolymer production technologies and associated terms. The most mentioned terms related to biopolymer technologies included cellulose, chitosan, starch, PHA, PLA, lignin, alginate, wheat, and soy.

Different actors were identified across the studies, covering a broad range of stakeholders from the supply chain. Academia was mentioned in more than half of the studies (57.4%). Overall, these studies identified the need for researchers to develop and increase knowledge in the field. Governmental and regulatory entities were also highly represented, mentioned in 39.8% of the documents. These data highlight the important role of research and scientific advancement, as well as the regulatory and policymaking actors, in the development and commercialization of biopolymer production technologies.

Considering the industrial sectors identified across the studies, we found that food and packaging industries were the most identified (45.5%), followed by the biomedical and healthcare industries (34.7%). Therefore, we found that most of the academic scientific production focused on these two big areas of actuation. This suggests that currently, these sectors might constitute the most substantial applications of biopolymer production technologies. Agriculture, aquaculture, and farming (18.8%), along with construction and engineering (10.2%) come next, followed by energy (9.7%), and textile industries (9.1%). Technology and manufacturing and waste management industries were the least mentioned, each one making up 7.4% of the documents (Table 1).

Table 1. Percentage of supply-side actors identified across the studies.

Stakeholders	Description	%
Academic and research industry	Research centers	57.4
Food and packaging industry	Food and beverages, food packaging, smart food packaging, dairy industry, and meat industry	45.5
Government and regulation	Governmental agencies, environmental protection agencies, and policymakers	39.8
Biomedical and healthcare industry	Medical device companies, pharmaceutical, drug delivery, and cosmetics	34.7
Agriculture, aquaculture, and farming industry	Agro-food sector, fertilizers industry, pest control, forest companies, wood industry, and marine biotechnology	18.8
Construction and engineering industry	Civil engineering, building and furniture, and concrete producers	10.2
Energy and environment industry	Biorefinery, bioenergy, and oil industry	9.7
Textile and fashion industry	Clothing, sport equipment, and footwear industry	9.1
Technology and manufacturing industry	Industrial machinery, electronic equipment, automotive, transportation sector, and communication sector	7.4
Waste management industry	Biomass, food waste management, and wastewater treatment	7.4

3.2. Barriers in the Commercialization of Biopolymer Technologies

Considering the barriers reported in the literature review, we grouped them into categories. The categories of barriers that emerged were technological, knowledge, economical, regulatory, supply stability, and behavioral related (Table 2).

Table 2. Multi-barriers identified across the studies.

Barriers	Description	e.g.,	%
Technological	Limited biopolymer properties, specialized equipment availability, and the need for diverse technical expertise	[11,43]	83.0
Knowledge	Limited research, gaps in farming techniques, lack of collaboration, and multidisciplinary approaches	[10,44]	56.8
Economic	High production costs and limited access to financial capital for research, development, and commercialization	[45,46]	47.7
Regulatory	Inconsistent policies and unique regulatory landscapes that complicate cross-border knowledge transfer	[19,47]	43.8
Supply stability	Limited raw material availability, seasonal variations, and resource management challenges	[48,49]	33.5
Behavioral	Resistance to change, intention–behavior gaps, market uncertainty, and perceived unacceptance from the demand side	[41,42]	18.2

Note. %—percentage of papers where the barrier was mentioned.

The majority (82%) of the documents mentioned more than one barrier. This finding reflects the common presence of multi-level barriers and the complex interaction between the different challenges that emerge in the commercialization of biopolymer technologies.

3.2.1. Technological Barriers

Technological barriers were the most mentioned challenge, emerging in 83% of the documents. This was expected considering that most documents were highly technical and from specialized areas of bioengineering and chemistry. These papers frequently tested the different biopolymer technologies through specific methodologies, such as life-cycle analysis.

Overall, we found barriers relating to the different physical and chemical properties of some biopolymers affecting their suitability for various applications, such as limited mechanical performance (e.g., bamboo fibers, gelatin, PHA, and lignin; [4,12,30]), thermal stability (e.g., agar, PLA, and poly[isosorbide]; [43,50,51]), and barrier properties (e.g., starch, cellulose, and chitosan; [11,32,52,53]). For example, significant impediments to the effective use of lignin as a high-value material include factors such as larger particle size, heterogeneity, asymmetrical morphology, and low dispersibility [4]. Its odor and color were also cited as factors that could restrict commercialization [54]. Another key challenge identified in the field of carrageenan-based delivery systems for bioactive components is the potential reduction in bioavailability during the preparation and delivery processes. To ensure that these bioactive ingredients are effective in providing their intended health or nutritional benefits, several issues related to the preparation and application of the delivery systems need to be addressed in the long term. These issues include carrageenan type, pH value, the ratio between biopolymers, crosslinking agents, and the sequence of material addition [55].

While biodegradable polymers present shorter degradation rates compared to traditional plastics, the end-of-life management is a crucial aspect that influences their overall environmental impact. The degradation rate of biopolymers depends on both their chemical structure and environmental conditions [20]. Limited recyclability and processes that might generate high volumes of waste (e.g., [56,57]) were also identified as significant issues. Waste management is a key challenge, as nonbiodegradable bioplastics can become contaminants when mixed with other polymers, and there is currently no effective separation process for recycling them [58,59]. To genuinely achieve a sustainable solution, it is essential to focus on the end-of-life management of each biopolymer, considering its potential for recycling or composting, rather than solely focusing on biodegradability [32,59].

Therefore, a key impediment to commercial adoption that we identified was the significantly different technical functionalities and production specificities that bio-based materials involve in comparison with petrochemical plastics [12]. Challenges in acquiring materials with comparable or superior properties to synthetic products were also mentioned. Particularly, achieving enhancements in barrier properties, thermal resistance, end-use mechanical properties, kinetics, and release [60]. Furthermore, bio-based companies, commonly characterized as niche markets, face the challenge of acquiring bioproducts. This task requires professionals with expertise spanning various domains, including engineering, mathematics, statistics, and biotechnology. Consequently, the need for individuals possessing this diverse skill set poses a considerable challenge in recruiting qualified human resources [61,62].

Besides potential constrained human resources, this category also included the limited availability of specialized equipment needed for production [18,63], limited technology development [64], low technological readiness [19], and a lack of technical strength or outdated technology [65]. For instance, in the case of extrusion-based 3D and 4D printing, technological difficulties have been reported. This included issues related to the time-consuming nature of the process [61], the precise adjustment of printing parameters [56,66,67], and a lack of biopolymer materials that can be applied to bioprinting [68].

Industrial scalability barriers were also mentioned, namely the lack of methods and technology for mass production or ability to effectively transform small-scale laboratory processes into larger commercial-scale processes [10,43,69–78].

3.2.2. Knowledge Barriers

Technological and industrial-scale implementation issues are intimately related to a gap between laboratory-scale research and practical applications [15,37]. Accordingly, it was mentioned that some sectors of the industry are some years away from transforming academic knowledge into commercial products. Therefore, the need for future research was also frequently mentioned across the studies. This was the second most mentioned challenge. It encapsulates insufficient knowledge or existing information on specific technologies, farming and production techniques, and the economic and environmental impact of biopolymer technologies [10,31,32,44,73,79–84].

In the context of scientific research, several biopolymer technologies were referred to as being in their infancy [64,85,86]. Lack of information about the behavior and quality of biopolymer products over time was mentioned. This factor is due to, in many cases, the novelty of certain technologies (e.g., marine biotechnology [38]). This barrier is identified as something that also affects skepticism and distrust among stakeholders, which are related to behavioral barriers and resistance to change. Therefore, it was mentioned that some of the disadvantages of bioplastics would be progressively overcome over time, through the development of new technology and further research [59].

Universities are emphasized as crucial players in advancing new technologies and knowledge. Meanwhile, companies and research institutes are anticipated to take on a more significant role in driving innovation in the sector [64]. Furthermore, the need for more comparative data about different biopolymer technologies was mentioned [87,88]. More life cycle assessment studies evaluating the environmental impact of various packaging materials, along with additional clinical trials in the biomedical sector [15,33], were also noted.

We found that the lack of knowledge and familiarity with some crops used to produce biopolymers that are perceived as relatively new did not appeal to farmers as much as the crops they already knew [19]. Furthermore, confusion and uncertainty regarding terminology and communication was also mentioned [89]. In line with this finding, the need for studies that consider the interaction of multiple aspects to promote the adoption of a biotechnology-based bioeconomy, including psychological, social, environmental, and economic aspects, was also mentioned [28].

Finally, the need for multidisciplinary and transdisciplinary approaches was pointed out as a key factor in overcoming the challenges of this industry. Collaboration, knowledge sharing, and cross-disciplinary research approaches were largely mentioned as imperative to the development and commercialization of biopolymer production technologies [42,60,74,76,90–92].

3.2.3. Economic Barriers

Economic hurdles were the third most mentioned aspect, in almost half of the documents analyzed. One of the key obstacles highlighted in the large-scale production of specific biopolymers is the significant associated cost (e.g., PHA [37]). More specifically, several authors have noted the absence of economically stable biopolymers for use in the industrial sector. They also highlight that commercial production and industrial-scale utilization continue to face challenges due to high production costs and labor expenses [17,45,46,52,93–101]. Particularly, the authors compare the higher cost of biopolymers in comparison to synthetic polymers [4,58,75,102–106]. For example, some authors mentioned that processing costs are still high considering that these biotechnological approaches are in the early stages of their development [107]. World market changes and price fluctuations were also mentioned [53].

In addition to production materials, the required production equipment was also described as capital intensive [56]. To this end, it is mentioned that the cost-efficiency, productivity, and competitiveness of biopolymer technologies need to be improved [48,108,109].

The limited access to financial capital for research, development, and commercialization was also identified as a significant challenge [38,40,67,110]. Moreover, the lack of incentives to encourage consumers to switch from conventional plastic products to more sustainable products is also mentioned as a barrier [6,111,112].

3.2.4. Regulatory Barriers

A key barrier identified across the studies was the complex regulatory landscape of biopolymer commercialization. Across different stakeholders, higher risks associated with the value chains included, besides their highly innovative nature, the lack of governance [19]. The lack of proper technical and governmental policies, regulations, and guidelines is a critical barrier. Additionally, gaps between policymaking and global implementation of new technologies, along with contradictory environmental policies, further hinder the development and commercialization of biopolymer technologies [23,27,35,36,47,83,110,113].

For example, the lack of a legislative framework for collecting and cultivating seaweed was mentioned as a significant impediment to the sector's development [38]. Furthermore, the lack of legislation by the government for legalizing certain raw materials, such as hemp, is also impeding farmers from having clearance for their cultivation [114]. Furthermore, the literature highlights gaps in awareness and policy measures to foster technological advancement and stimulate demand. Additionally, there is a noted lack of long-term vision and consensus on the optimal path for transformation [62].

Challenges related to pre-market approval and environmental protection regulations were identified [115,116]. This is especially true when using residual streams for biopolymer production, which can introduce additional complexities in terms of waste management and regulatory oversight. The lack of adequate legislation and recycling practices for residual streams can hinder the efficient and sustainable use of these materials. Therefore, the development of clear regulatory frameworks and the promotion of comprehensive recycling practices are crucial in addressing these challenges and ensuring the successful commercialization of biopolymers derived from residual streams [6]. Additionally, we found concerns and deep considerations with social and ethical issues to meet the complex regulatory challenges regarding national food safety regulations, health, and consumer acceptance [78,109,117–119]. For instance, we found concerns regarding unwanted effects on taste and sensory properties and concerns related to reducing the transfer of tannins into food or preventing the release of by-products resulting from their interaction with food components. Addressing these considerations is crucial for meeting regulatory requirements in the food packaging sector [120].

Another important aspect mentioned is that each country possesses a distinctive environmental and regulatory framework, making it challenging to apply the insights gained from policy implementations in one country to another [42,74]. This lack of updated global and specific regulations and laws prevents the further development of new biopolymer technologies. As such, updated and shared regulations and laws are necessary to guide research and manufacturing [18], and promote the development and commercialization of biopolymer technologies.

3.2.5. Supply-Stability Barriers

The limited availability of consistent and high-quality raw materials was also identified as an important barrier. The shortage of specific materials presents a challenge in expanding the application of certain biopolymer production technologies. For instance, the shortage of polyamino acids (PAAs) in optical and piezoelectric sensors, as well as in immunoassays, gene sensors, and peptide-based sensors, and APTA-assays, presents a challenge in expanding the application of PAAs in these areas of the biomedical industry [29]. Furthermore, shellfish, the primary source of chitin and chitosan—and with potential applications in the food, biomedical, and industrial sectors—also faces challenges related to supply chain reliability and seasonality issues in their availability [49].

The dependence on external factors including climate factors, seasonal variations, disease and pest control, and susceptibility to pesticides can affect crops' adaptability and the consistency and quality of the production [16,19]. These external factors can affect raw material availability, or supplies of raw material, which might occasionally fluctuate both in availability and price [48,88,99]. The need to optimize and scale up the purification process for some products (e.g., chitin) and develop procedures to enhance its properties was also highlighted. These challenges can impact the supply chain of the biopolymer and its derivatives by affecting the availability and quality of these materials [49].

Moreover, several challenges related to the recovery of agri-food waste and by-products that are critical for the growth of the industry were mentioned. The potential of managing waste for packaging development relies on region-specific factors. These include the availability of suitable facilities for waste management, recovery, and recycling, as well as the seasonality of products that contribute to waste generation. Therefore, some biorefineries cannot work with large feedstock volumes due to the seasonality of some products. It is also relevant to note that it is still not known what the optimal approach is to centralize waste management. In cases where logistical expenses outweigh the value of the biomass, biorefineries may choose to avoid these costs by resorting to incineration or landfills for waste disposal. To address these issues, the adoption of a circular bioeconomy model offers a solution, allowing for the revaluation of food waste, by-products, and biomaterials generated by biorefineries, ultimately mitigating these challenges [43].

Concerns regarding the possible depletion and dwindling of some resources from forests were also found (e.g., wood; [53]). Therefore, sustainable resource management planning, infrastructure development, and identification of potentially available land are challenges identified as critical to ensure an adequate supply of agricultural goods for the bio-based economy [28]. Additionally, despite the diversity in the market, only a few producers are identified [96], and there is a lack of crop diversification and job opportunities [19]. Land managers were identified as the principal actors determining how much land would be allocated for biomass production. Market demand for feedstock and their confidence in the stability of the supply chain will impact on the decision-making processes of these stakeholders [42].

3.2.6. Cultural/Behavioral Barriers

While technical feasibility is mentioned as one fundamental aspect, the commercialization of new technologies also faces cultural and behavioral challenges that must be overcome [62]. We found cultural and behavioral barriers in 6% of the reviewed documents. This category includes resistance to changing traditional practices and production methods. We found that the transition to a 'biobased society' is perceived as a significant challenge [41]. Resistance to adopting new practices and technologies was related to perceived risk of loss, the absence of sustained market predictability, upfront investments, enduring land commitment, and the risk of potential crop shortfall, along with immature markets and perceived limited number of end-users [42].

In some cases, it was mentioned that entrepreneurs lack good practices, models, and experiences [121]. The changing market trends and technological advancements were also identified as considerable barriers. Organizations also need to stay updated on technological and market trends, as well as on the benefits of transitioning to a circular economy [122].

Individual characteristics also emerged, with age and level of education being identified as a barrier. It was found that older farmers are more unwilling to change and are resistant to altering their conventional farming methods, often as a result of a lack of understanding of market dynamics. Moreover, farmers with lower educational levels are less inclined to participate in circular markets [62]. We also found difficulties associated with appraisal of the potential benefits of certain biopolymer technologies, such as natural fiber-reinforced composites (NFRCs) in civil engineering applications, including uncertainties about their properties and a lack of understanding among civil engineers of the material and their life cycle [123].

Another challenging aspect for supply-side actors is their perceptions of consumers' attitudes. We found that the concept of 'bio-based' is still unfamiliar for many segments of consumers, and their perceptions towards this concept are diverse. It was associated with both positive and negative environmental aspects, indicating a lack of knowledge and information among consumers [124]. Lack of customer interest or knowledge about the benefits of green products [65] were the main challenges identified. Furthermore, the novelty of some sectors creates skepticism and a poor level of engagement among stakeholders, including government, promoters, scientists, regulators, manufacturers, and consumers. This lack of engagement can hinder the sector's development [38]. The authors discuss the need to develop incentives to promote consumers to switch from conventional plastics to biobased plastics [6], and to demonstrate to skeptical consumers the advantages of nature-derived products over traditional ones [77]. Although the previous barriers are typically associated with the demand side, consumer perceptions significantly affect supply chain operators. This is seen, for example, in the resistance to changing traditional practices due to the perceived restricted quantity of end-users and unpredictability in the long-term market landscape. Furthermore, gradual growth in market demand and acceptance among consumers may result in elevated production costs, affecting the supply chain [12].

Safety perceptions were also suggested as a critical barrier. A large segment of consumers are highly concerned with product safety and security, implying that any new biopolymer technology introduced into the market needs to address these concerns. This adds a layer of complexity to the adoption of biopolymer-based solutions, as they must not only be effective, but also perceived as safe by consumers, particularly in the food industry [31].

Therefore, the market adoption and integration of new biopolymer technologies need to be thoroughly managed [125]. First, there is a need for strategies aimed at informing both customers and organizations on the proper management and classification of bio-based products. The role of Life Cycle Assessment (LCA) is crucial in this process, as it provides a comprehensive evaluation of the environmental impacts associated with biopolymer production. LCA can guide both organizations and customers in making informed decisions, ensuring that bio-based products are properly classified and meet sustainability standards throughout their life cycle. In this vein, the term "greenwashing" is used to describe how the labeling of products as natural, biodegradable, or compostable without proper adherence to such claims can be misleading for consumers [20]. To overcome this barrier, clear and understandable communication, tailored to consumers who are somewhat hesitant and distrustful of accepting new technologies in general, and new biopolymer technologies in particular, is essential [118]. There is a clear need for evidence-based information campaigns to educate stakeholders on the risks and limitations associated with new biopolymer technologies [63]. Additionally, efforts should focus on increasing public awareness of the personal benefits of new biopolymer products [126]. Such campaigns should be iteratively tested with members of the intended audience, and their results monitored [127]. Furthermore, it is relevant to extend existent knowledge to better understand biopolymers' large-scale applications [48] and develop identifiable leading products that can attract and maintain the attention of the market [33]. Finally, responsible innovation approaches, stakeholder accountability, and community engagement are needed to gain public acceptance [74].

4. Discussion

Although biopolymer technologies are advertised as sustainable alternatives to traditional linear plastics, their path to widespread adoption is hindered by several challenges. The systematic gathering of information pertaining to the barriers of commercializing biopolymer production technologies represents a critical step towards understanding the complex landscape of sustainable materials in today's world. Biopolymers, often derived from renewable resources, hold immense promise in reducing our reliance on fossil resources. Therefore, their use represents a significant step towards achieving sustainability goals by reducing environmental impact [7].

The present work aimed to provide a comprehensive analysis of the multi-level barriers across a broad range of stakeholders from the supply chain, including researchers, policymakers, and industry professionals. The focus was specifically on understanding the obstacles hindering the commercialization of new biopolymer production technologies as a first step toward drafting recommendations to overcome them.

Multiple key actors emerged across the studies, providing a comprehensive overview of the barriers across different stakeholders from the biopolymer supply chain. The results highlighted that the majority of the documents identified multiple barriers, illustrating the complex interactions between various challenges in the commercialization of biopolymer technologies. Additionally, we found that technological and knowledge barriers were the most mentioned, followed by economic, regulatory, supply stability, and behavioral barriers.

Overall, we found that the successful commercialization of biopolymer production technologies remains a challenge, mainly characterized by a segmented and underexplored body of literature. One significant problem in grasping the barriers to biopolymer commercialization is the fragmentation of the relevant studies. The literature on this topic is still scattered across various academic domains and industries, making it difficult for stakeholders, researchers, and policymakers to access and synthesize the available knowledge. As a result, efforts to streamline and compile this information are crucial for advancing the field. Therefore, to overcome these challenges, there is a need to adopt multidisciplinary and transdisciplinary research approaches, and foster collaboration, coproduction, and knowledge sharing between stakeholders [74,76,91].

Moreover, we found the scarcity of studies directly and specifically examining barriers related to the commercialization of biopolymer production technologies to be a notable concern. As mentioned, most of the documents were from the bioengineering field, providing highly specialized data on the technical development of biopolymer production technologies. This scarcity may also be attributed to the fact that many studies in this area include sensitive commercial information. Much of the research related to the commercialization of biopolymers may be conducted within companies or initiatives, but is not shared in scientific publications due to concerns over intellectual property, competitive advantage, and confidentiality. Therefore, in many instances, the focus of the existing literature leaned heavily towards technological barriers. However, the commercialization of biopolymers involves a multitude of other factors, including regulatory hurdles, market dynamics, supply chain challenges, and behavioral–psychological barriers that require considerable reflection. While there is some information available in the form of technological papers that touch upon these barriers, they often relegate these discussions to the limitations section, offering only cursory insights into the challenges faced in the biopolymer industry.

Despite our comprehensive analysis, it is essential to recognize that the barriers we have identified in the literature may not fully capture the nuanced challenges present in the industry. Therefore, to bridge this gap and enable the successful commercialization of biopolymer production technologies, there is a pressing need for more research that delves into the full spectrum of barriers and directly collects these data across different stakeholders. A comprehensive understanding of these barriers requires examining the perspectives of a wide range of actors, including researchers, product developers, manufacturers and industry professionals, retailers, policymakers, and environmentalists, without forgetting the articulation of consumer perceptions. More in-depth inputs regarding sociopolitical and behavioral variables, collected through the classical social sciences methodologies, such as interviews or questionnaires across different stakeholders, are needed. Therefore, it would be relevant to develop further studies gathering direct insights from the perceived barriers identified from the multiple key players across the supply chain, to obtain a better understanding of the main challenges experienced by these players.

To overcome the barriers identified in this study and facilitate the adoption of biopolymers in large-scale industrial applications, it is essential to propose practical measures that address the existing challenges. Firstly, there is a need for more intensive and interdisciplinary collaboration among researchers, policymakers, industry professionals, and other relevant stakeholders. Such collaboration should focus on the co-production of knowledge and solutions that encompass not only technological challenges, but also regulatory and market-related obstacles, fostering more integrated approaches to the adoption of biopolymers. Additionally, the development of clear and harmonized regulatory guidelines specifically tailored to biopolymers is fundamental to streamlining the approval and certification processes for biopolymer production technologies. This standardization not only facilitates market entry, but also fosters investor confidence in the sector.

Another crucial aspect is strengthening resilience in the supply chain. Strategic investments should be made to diversify raw material sources, particularly by leveraging agricultural by-products and organic waste as viable alternatives. This approach reduces dependence on plant-based materials subject to seasonality and climatic conditions, while also contributing to the transition toward a circular economy. Furthermore, it is imperative to provide greater financial incentives and targeted support for the development of biopolymer technologies. Governmental and private funding should prioritize research, technological development, and commercialization efforts, complemented by tax benefits and subsidies to encourage industries to transition to more sustainable practices.

Finally, informational and awareness-raising campaigns must be promoted to increase market acceptance and demand for biopolymers. Public and industrial awareness of the environmental benefits of biopolymers plays a central role in creating a favorable market, which, in turn, drives investments and advances in the field.

The implementation of these measures can significantly contribute to mitigating the identified barriers and creating a more favorable ecosystem for the integration of biopolymers into industrial applications, promoting tangible progress toward sustainability goals.

5. Conclusions

The pursuit of accepting and advancing sustainable biopolymer production technologies holds profound significance in transitioning toward a circular economy. This systematic review has underscored the critical barriers impeding this advancement. Our effort was to synthesize and organize the existing fragmented literature on the topic of new biopolymer production technologies and the challenges hindering their adoption, to create a valuable resource for all stakeholders involved in the transition to more sustainable materials and practices. We found barriers encompassing technological complexities, knowledge gaps, economic constraints, regulatory challenges, supply stability issues, and cultural resistance. Recommendations include addressing these obstacles with interdisciplinary collaboration to forge a cohesive regulatory framework. Intensified research efforts are essential to bolster environmental protection and safety standards, alongside implementing public policies that incentivize consumer adoption of bioplastic products. Moreover, regulating labeling practices to prevent misleading strategies is pivotal in fostering consumer trust. Furthermore, the importance of collaboration and multidisciplinarity cannot be overstated in enhancing knowledge and technological advancements in biopolymer research. By bridging diverse expertise and perspectives, stakeholders can collectively navigate regulatory complexities and propel sustainable innovation. These insights not only provide an overview of the existing challenges, but also provide a valuable roadmap for navigating the complex landscape of biopolymer commercialization. Therefore, these findings have the potential to inform future research, policymaking, and commercial interventions in this field.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17030820/s1.

Author Contributions: Conceptualization, C.P., A.R.F., S.D., B.C., S.L. and A.L.; methodology, C.P., A.R.F., S.D. and B.C.; formal analysis, C.P., S.D. and B.C.; investigation, C.P., S.D. and B.C., data curation, C.P., S.D. and B.C.; writing—original draft preparation, C.P.; writing—review and editing, C.P., A.R.F., S.D., B.C., S.L. and A.L; supervision, C.P. and A.R.F.; funding acquisition, A.R.F. All authors have read and agreed to the published version of the manuscript.

Funding: This work received funding from the European Union's Horizon 2020 research and innovation program under grant agreement no. 101099487—BioLaMer-HORIZON-EIC-2022-PATHFINDEROPEN-01 (BioLaMer). This work was funded by Fundação para a Ciência e Tecnologia (FCT), under HE Lab R&D Unit (UIDB/05380/2020, https://doi.org/10.54499/UIDB/05380/2020).

Conflicts of Interest: The authors declare no conflicts of interest.

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