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Review

A Systematic Review on Biosurfactants Contribution to the Transition to a Circular Economy

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Abstract: Since they are more environmentally acceptable than their chemically synthesized counterparts, biosurfactants are used in a wide range of environmental applications. However, less research has been done on biosurfactants within the context of the circular economy, despite their theoretical potential to fulfill a number of circular economy ambitions, including closing the consumption loop, regenerating natural systems, and maintaining resource value within the system. Hence, the main objective of this review is to identify and analyze the contributions of biosurfactants to the implementation of the circular economy. A final sample of 30 papers from the Web of Science database was examined. We identified five broad categories of contributions: waste stream-derived production, combating food waste, strengthening soil health, and improving the efficiency of water resources. We concluded that, while manufacturing biosurfactants from waste streams can reduce production costs, optimizing yield remains a contentious issue that complicates the adoption of biosurfactants into the circular economy framework.

Keywords: biosurfactant; microbial conversion; biomass; circular economy; sustainability

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1. Introduction

Biosurfactants are amphiphilic compounds found on the surfaces of microbial cells that contain polar and non-polar moieties that allow them to form micelles that assemble at the interface of fluids with different polarity (e.g., water and oil), thus reducing surface pressure. Their structure may include glycolipids, mycolic corrosive, polysaccharide–lipid composite, lipoprotein/lipopeptide, phospholipids, or the microbial cell's own surface. Biosurfactants are produced by a variety of microorganisms such as yeast, fungi, or specific bacterial strains [1–3].

Chemically synthesized surfactants (from petroleum derivatives) have environmental restrictions due to their toxicity and lack of biodegradability. As a consequence of these concerns, interest in biosurfactants as non-toxic and biodegradable substitutes has increased significantly. Hence, what makes biosurfactants particularly important in the context of global efforts toward sustainable development is that, from an ecological standpoint, they are non-toxic, biodegradable, and exhibit greater effectiveness under a variety of extreme conditions, such as temperature, pH, salinity, and show environmental acceptability when compared to chemical surfactants [4,5].

In the 1960s, hydrocarbon breakdown operators began to utilize biosurfactants more frequently, and their uses have grown considerably over the last five decades as an improved alternative for surfactant compounds, particularly in the food industry. Nowadays, it is projected that every year, over 10 million tons of compound surfactants and microbial biosurfactants are delivered [2,6].

Biosurfactants have numerous environmental applications, including oil spill bioremediation and dispersion, increased oil recovery, and crude oil transfer. Other possible biosurfactant applications include the food, cosmetic, medicinal, and agricultural industries. These compounds also have a propensity for being multifunctional agents: wetting agents, antibacterial agents, emulsifiers, or anti-adhesive agents [7,8].

However, increasing the volume of sustainable biosurfactant production requires an integrated economic process that includes waste reduction, reuse, and recycling. Circular economy could be a viable option, since it would allow for the development of a new technology-oriented economy with high employment potential and low environmental impact by using biobased feedstock instead of imported fossil fuels to produce materials, chemicals, and energy. This is particularly important, because aside from minimizing the environmental and economic implications of waste disposal, one current global challenge toward sustainability is to recover as much energy and materials as possible from waste streams, thereby adopting a circular economy with the greatest potential added value [9].

Despite the significant potential that biosurfactants hold in the process of shifting toward a circular economy (e.g., using waste as a source of raw materials to create the bio-surfactant, oil recovery, bioremediation, etc.), their contribution to this issue is currently underexplored in the literature. The notion of green economics [10,11] and unconventional sources of biosurfactants [12,13] have received the majority of attention in published articles on this topic thus far, as opposed to the circular economy concept itself. In light of these observations, this review has the following goals:

1. Identify and assess the role that biosurfactants play in the circular economy.
2. Develop future research directions that take into account biosurfactants integration in the circular economy framework.

2. Main Characteristics of Biosurfactants

The majority of biosurfactants generated are glycolipids. They are sugar-aliphatic acid or long-chain hydroxyaliphatic acid compounds. The association is made by methods of collecting either the ether or the ester. Rhamnolipids, sophorolipids, and trehalolipids are the most well-known glycolipids.

Microbial oxidation of alkanes results in the formation of fatty acids [14]. Microorganisms produce complicated fatty acids with OH groups and alkyl branches in addition to linear chain acids. Phospholipids are essential components of microbial membranes [15]. Phospholipid levels rise when hydrocarbon-degrading bacteria thrive on alkaline substrates. Lipoproteins and lipopeptides, on the other hand, refer to decapeptide antibiotics (gramicidins) and lipopeptide antibiotics, respectively (polymyxins). They have a lipid attached to a polypeptide chain [16]. Figure 1 depicts the main types of biosurfactants based on their molecular mass.

Biosurfactants are mostly created by aerophilic microorganisms in aqueous media using carbon sources like hydrocarbon, polysaccharides, lipids, and oil derived from bacteria [17–19]: (*Pseudomonas*, *Bacillus*, and *Acinetobacter*), fungus (*Aspergillus* and *Fusarium*), or yeast (*Candida* and *Pseudozyma*).

Several environmental and operational factors, such as the carbon and nitrogen source, carbon to nitrogen ratio, minerals, metabolic regulators (inhibitors and inducers), or salinity, have an impact on the synthesis of biosurfactants [20]. Nevertheless, carbon substrate is critical in biosurfactant creation and has a substantial impact on yield and quality, which can be split into the following categories: carbohydrates, hydrocarbons, vegetable oils, and hydroxyl compounds, usually polyols [21]. Hydrocarbons have traditionally been the favored substrates for the manufacture of biosurfactants and bioemulsifiers. The usage of hydrophobic substrates is thought to cause the synthesis of biosurfactants, making the hydrophobic substrates more accessible to the producing microbial cell. Water-soluble substrates, on the other hand, have been used [22]. Because monophasic fermentations are simpler than biphasic fermentations, they are less expensive and are favored as a substrate over hydrocarbons. Furthermore, hydrocarbon-containing substrates are unsuitable for a wide range of applications, including those in the food, cosmetic, and pharmaceutical industries. Fats, oils, glycerol, and carbohydrates are examples of non-hydrocarbon substrates. Carbohydrates and vegetable oils are two of the most commonly used substrates for biosurfactant synthesis [22,23].

Due to the complexity of the down-stream processing and high expenses required in microbial cultivation to biosurfactant recovery (cultivation, production, purification, and recovery), industrial-scale biosurfactant manufacturing is still in its infancy compared to their counterparts, surfactants of petrochemical origin (Table 1).

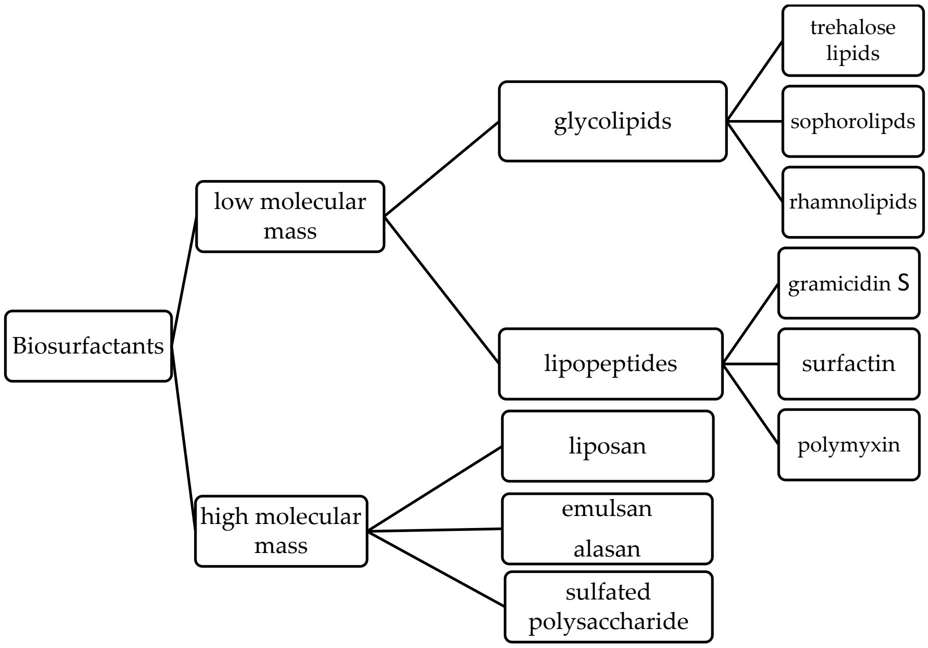

Figure 1. Main types of biosurfactants by molecular mass.

Table 1. Differences between biosurfactants and surfactants.

Comparison Criteria	Surfactant (Petrochemical Origin)	Biosurfactant (Microbial Origin)
Costs	Low, suitable as enhanced oil recovery (EOR) [24], which needs significant volumes of low-priced surfactants	High productions cost, suitable for low volume and high costs products (cosmetics industry) [25]
Environmental impact	High toxicity Low biodegradability Low environmental compatibility	Low toxicity, High biodegradability, High environmental compatibility
Industrial applicability	Used in a variety of products requiring very high volume of surfactants domestic and industrial applications [26]	Not yet widely employed in industrial production because they require expensive substrates with relatively poor productivities, limiting their commercial usage

In most biotechnological processes, raw materials are expected to account for 30–40% of overall production costs. As a result, it is preferable to employ low-priced raw materials to lower this expense. One of the large-scale options being investigated is the use of low-cost (organic-rich) raw materials derived from agro-waste or industrial waste as substrates for biosurfactant manufacturing [4]. Although genetic engineering can boost biosurfactant output, consumers remain generally reluctant to the usage of genetically modified species [27,28].

Nonetheless, despite continuous improvement of fermentation processes, the most promising breakthrough in the field of biosurfactants is expected to occur on the molecular level: future advances in genomics, transcriptomics, and metabolomics will enable to further elucidate the complete biosynthetic pathways and their regulation, as well as provide more insights into general lipid metabolism of producing strain. For example, regarding glycolipids, it is still unclear how they are regulated, as well as how glycolipid production relates to overall lipid metabolism. The type of carbon source may affect the glycolipid biosynthesis process' choice of lipid metabolic pathway [29]. Additionally, high carbon-to-nitrogen ratios, nitrogen exhaustion, stress conditions, and high cell densities are other characteristics that support high levels of production [30].

3. Circular Economy and Biosurfactants

By lowering material intake, increasing product usability, and reducing waste generation, a circular economy aims at decoupling economic growth from resource use. Closing the loops seeks to address the issues of resource scarcity, biochemical fluxes, and climate change while providing communities with regenerative and restorative benefits. When compared to sustainability, circularity is a much more recent approach, with a greater focus on reducing system inputs, enhancing and preserving natural resources, effectively managing finite resources, and lowering overall risks [31,32]. The circular economy can be applied at a microeconomic level (individual consumers), macroeconomic level (industrial parks), and macroeconomic level (locality, region, country, etc.). Hence, the framework for a circular economy not only diminishes the number of raw materials used within the system but also creates opportunities for sustainable consumption, waste management, and innovation across all industries, as well as for human development and increased well-being for everyone [33,34].

The circular economy and biosurfactants are linked by the concept of exploiting waste to produce valuable material. Since biosurfactants may be synthesized from waste, they contribute to closing the consumption loop, leaving less waste behind and, as a result, minimizing the production's carbon footprint [35]. Using biosurfactants in industry benefits both the circular economy and sustainability goals, as well as economic operators. From an economical standpoint, using waste for biosurfactant synthesis has various advantages, including reduced processing costs and the ubiquitous availability of many less expensive or renewable substrates. From a circular perspective, the product becomes more environmentally friendly and resource efficient while retaining its core functioning features. The creation of biosurfactants, however, faces several difficulties in regard with the biological source, and research [36,37] has demonstrated that these issues can be addressed by further examining various microbes and plants as substitute sources.

Consequently, we can discuss a synergistic link between biosurfactants and the circular economy: waste processing in the circular bioeconomy produces an equilibrium among industrial processes, economic prosperity, and environmental security while enhancing resource allocation. Furthermore, biosurfactants' enhanced production from inexpensive and renewable sources, as well as their stability and biodegradability, demonstrate their contribution to improving sustainability and circular bioeconomy [20].

4. Methodology

In order to generate new insights, ideas, or models, a systematic review must integrate all empirical facts on a subject that satisfy a set of predetermined criteria. The core of a systematic review is using an explicit and reproducible procedure to identify all the studies that fulfill the predetermined eligibility requirements. We considered the following exclusion criteria during the screening process, since the purpose of this study is to analyze the contributions that biosurfactants bring to the implementation of the circular economy and to suggest future research areas in this area:

- Papers published in conferences, patents, technical reports, book chapters;
- Papers that did not clearly define their data sources or with unclear methodology; Papers not published in English;
- Papers published before 2010;
- Papers that are not relevant to the stated objectives.

The methodological approach is depicted in Figure 2. The preliminary search yielded a number of 75 papers. We considered alternate concepts for the circular economy keyword, such as green economy or sustainability, to maximize our chances of retrieving all relevant publications that meet the predefined criteria. A final sample of 30 papers was obtained after applying all the aforementioned criteria and performing the complete paper screening. The relevant papers are listed in Appendix A along with their source, keywords, and year of publication.

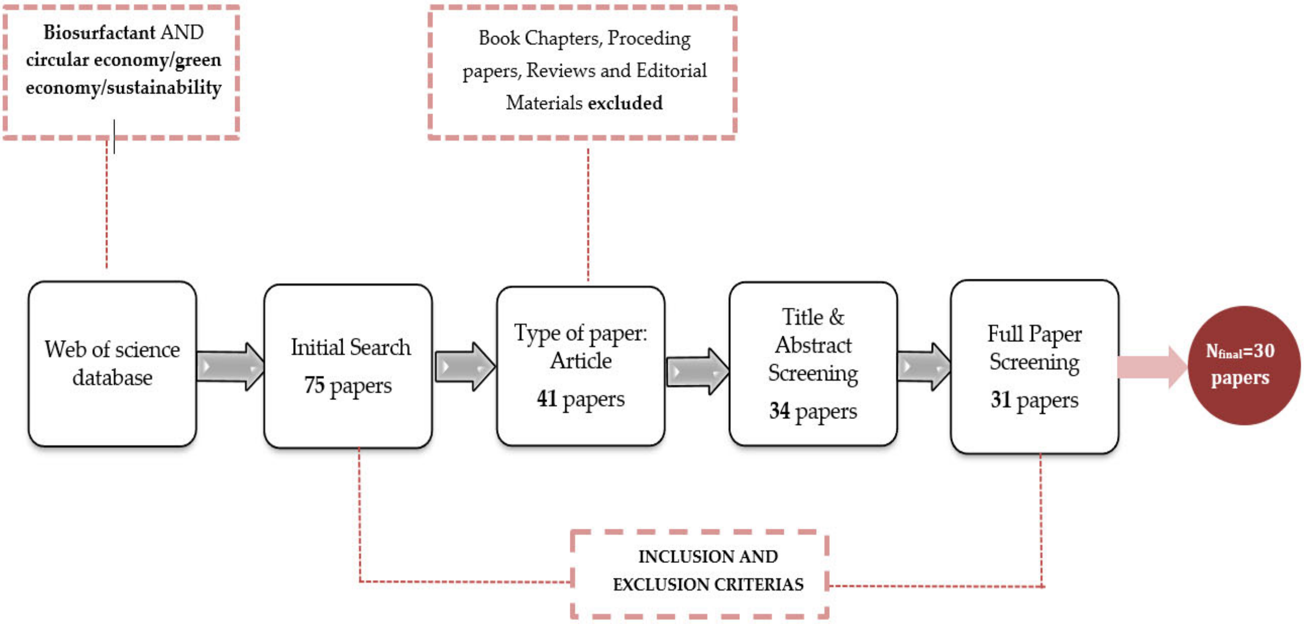

Figure 2. Methodological approach.

5. Results

After evaluating the sample of papers comprised in Appendix A, we managed to identify and analyze what are the main contributions of biosurfactants in a circular economy. We concluded on 5 types of contributions: waste stream-derived production, combating food waste, increasing water resource efficiency, soil bioremediation, and boosting soil health. Table 2 summarizes these findings, and highlights the associated circular economy principle, as well as papers from the final sample demonstrating the respective contribution of biosurfactants.

Table 2. Main contribution of biosurfactants to the circular economy.

Biosurfactant Contribution	Circular Economy Principle	Source
Waste stream-derived production	Closing the loop To coexist in a sustainable manner, society and the biophysical environment must both be seen as open systems. Resources should be removed and restored to the ecosystem at rates that are below the Earth's ability to replenish and absorb them [38].	[39–42]
	Eliminate waste and pollution In a circular economy, waste must be regarded as a design defect of our consumption system. A requirement for any design in a circular economy is that the materials re-enter the economy after being used, thus converting the take-make-waste system from linear to circular.	[43–46]

Table 2. *Cont.*

Biosurfactant Contribution	Circular Economy Principle	Source
Combating food waste	Maintaining resource value within the system Shifting away from producer-driven consumerism and replacing it with provisioning systems that enable responsible, demand-driven resource use in addition to increasing sharing, service, and experience-based consumption [47].	[48–54]
Increasing water resource efficiency	Reduce and decouple resource use Reinforce resource sufficiency, efficiency and dematerialization through policies and actions that disconnect wellbeing from unsustainable resource use.	[55–60]
Soil bioremeditation Boosting soil health	Regenerate nature Instead of perpetually deteriorating nature, we must use practices that allow nature to repair soils, increase biodiversity, and replenish biological materials in the earth.	[61–67]

From a broad perspective, the sample analyzed revealed that in a circular economy context, biosurfactants have a number of benefits that enable their usage in highly polluted environments. According to the literature [40,45], there are three methods to employ biosurfactants: as a crude extract, pure biosurfactants, or as a product of microorganisms that produce biosurfactants.

Concerning the first contribution, waste stream-derived production, a range of low-cost waste materials were examined as substrates for the manufacture of biosurfactants in recent years. Worldwide, millions of tons of hazardous and non-hazardous waste are produced each year. For instance, in the European Union, each person produced 4.8 tons of garbage in 2020. Throughout the European Union in 2020, 31.3% of waste was disposed of in landfills, while 39.2% of waste was recycled [68]. Numerous industries are heavily burdened financially by the price of treating and disposing of these wastes, which may quickly exhaust available resources. Better waste management is therefore urgently required [12]. This led to the continuous development of an efficient cost-cutting strategy for biosurfactants connected with efficient waste management [69]. Hence, there is a huge potential for producing biosurfactants from a variety of affordable, renewable industrial wastes in order to close the loop of consumption and production [70]. Waste produced from several sources, including oil, agro-industries (lactic whey, molasses), distilleries, and others, has been successfully used as a feedstock for the manufacturing of biosurfactant [42].

Another important aspect to point out from our analysis is that the selection and accessibility of substrate are significant issues in the environmentally acceptable synthesis of biosurfactants. However, numerous efforts have been made to satisfy the demand for inexpensive substrates for the manufacturing of biosurfactants. In this context, there is a great potential, as substrates for the synthesis of biosurfactants were greatly enhanced by agro-industrial and food waste. *Pseudomonas aeruginosa*, *Bacillus licheniformis*, *Halobacteriaceae archaeon*, and other common microbial species have been effectively used to produce biosurfactant from agro-industrial waste, including maize steep liquor, date molasses, orange peel, and sugarcane bagasse. Another eloquent example is the case of frying oil. Large amounts of frying oil are generated for usage in the domestic market and in the food sector. When cultivated on used olive oil or used sunflower oil, *Pseudomonas* strains grew effectively. Olive oil was found to be a better substrate for cell growth and biosurfactant synthesis [71]. All of these solutions reduce waste while also providing a way to profit from the biosurfactant market [20].

Concerning the third contribution, a consistent idea from the sample analysis is that biosurfactants can boost the efficacy of water resources. Bio-based surfactants can be employed to improve the treatment of heavy metal-contaminated soil and water. Biosurfactants also have applicability as biocomposite agents and bio-adsorbent in the context of wastewater treatment [36,72]. Moreover, oil leaking into the ocean is a serious issue that threatens to damage coasts. The problem of oil spills may benefit from biosurfactants since they may be less harmful and tenacious than synthetic surfactants. According to Chakrabarty [73], *Pseudomonas aeruginosa*'s emulsifier can spread oil into tiny droplets that can speed up biodegradation [74].

Finally, biosurfactants contribute to the circular economy by being employed for soil remediation and overall soil health improvement, thereby assisting in nature's regeneration. Bioremediation is an emerging method that incorporates biological degradation or removal of organic pollutants under controlled environmental circumstances. In this way, toxic contaminants are reduced, degraded, detoxified, mineralized, and transformed as part of the bioremediation mechanism [42]. It has been demonstrated that the presence of higher doses of rhamnolipid promotes the degradation of petroleum hydrocarbon-contaminated soils [62]. Furthermore, several studies [3,62] suggest that the application of biosurfactants can enhance soil health. *Pseudomonas* and *Burkholderia* species-derived biosurfactants may be employed as secure biopesticides. These insecticides can be made using any type of surfactant, including cationic, anionic, anionic, and amphoteric ones. Surfactants are used by agronomists to increase the antibacterial activity of microorganisms. The significance of surfactants in enhancing insecticidal abilities has been demonstrated by several in vitro and in situ investigations [75].

From a practical standpoint, based on the study sample analyzed, we note that the use of agro-industrial waste and food by-product streams as renewable resources for starting fermentation feedstock is the best strategy in terms of potential to lower the price of biosurfactants [76]. Among the earliest suggested applications of biosurfactants were enhanced oil recovery and bioremediation. Additionally, the application of biosurfactants in the circular economy context has taken on increasing prominence as novel formulations are sought to venture the cosmetics, pharmaceutical, and food industries. A summary of the main practical applications identified is presented in Table 3.

Table 3. Biosurfactants input to industry from a circular economy perspective.

Type of Biosurfactant	Potential Circular Economy-Focused Application in the Industry	Sources
Glycolipids	Enhancing microbial electrochemical treatment of petroleum hydrocarbon contaminated soil through rhamnolipids	[62]
	Crude microbial bioremediation of offshore marine oil	[45,59]
	Merging industrial waste streams or by-products to sophorolipids fermentation has mutually beneficial effects as these inputs are abundantly available, and using waste streams for sophorolipid production improves recycling and reusing, achieving effective waste management	[77]
	Treatment of heavy metal contaminated wastewater	[8,57]
	Efficient recovery of residual oil from intensive exploited reservoirs	[78]
	Enhancing the bioavailability of hydrocarbons through trehalolipids	[79]
Lipopetides	Lipopetides act as bioremediation agents for soils, surface water, groundwater, and waste streams contaminated with hydrophobic organic compounds, such as metals and polycyclic aromatic hydrocarbons, hence they are linked to an improvement in soil quality, which is essential for the development of crops.	[40,43]
	Crude oil remediation by bioelectrokinetic technique	[8,40]
	Treatment of heavy metal contaminated soil	[71]

Therefore, two major interaction mechanisms underlie biosurfactant environmental applications in the circular economy. First, the presence of biosurfactants increases the bioavailability of the substrate. Secondly, by enhancing its hydrophobicity, it improves interaction with the cell surface, facilitating hydrophobic substrates to associate with bacterial cells [79,80]. Finally, another important insight obtained from the study sample is that the ability of microorganisms to create biosurfactants in situ is still largely unexplored, as the majority of the reported investigations were carried out in a laboratory setting.

6. Discussion

6.1. Further Research Directions

As an overarching observation, there are many potential uses for biosurfactants due to their better biocompatibility and microbial biodegradability. This is especially the case when there has been significant environmental intervention, such as in the decontamination of oil-polluted areas, tertiary petroleum recovery, crop protection, and the cosmetic and pharmaceutical industries [80]. As a result, it is not surprising that a number of studies have been conducted in order to uncover the synthesis of such chemicals with potential applications in bioremediation, agriculture, and industry [45]. The preceding section demonstrated that biosurfactants can be an enabler for the transition to a circular economy through their various applications in accordance with the circular economy system: closing the resource loop, regenerating natural systems, and even preserving resource value within the system.

Although producing biosurfactants from waste streams lowers production costs, optimizing yield remains an important field of research due to the heterogeneity in producing strains and desired products [10]. Therefore, engineered processes for improving waste to biosurfactant production have to be further developed. For example, in order to increase the production and quality of the biosurfactant product, strategies including green chemistry and genetically engineered microorganisms are applied. Even though pretreatment of renewable substrates facilitates organism growth, caution must be taken to preserve the nutritional benefits of such substrates, since the product must be high quality and quantity in order to open up a wide range of industrial prospects for surface active agents of microbial origin. There is still a lot of potential for wastes from the dairy, animal fat, and food processing industries [69]. Furthermore, another aspect to consider for future research is that high biosurfactant concentrations must be employed with caution due to their biocidal activity and potential enzymatic inhibition, which hinders the remediation process and reduces microbial diversity [80].

Concerning the food industry, we believe that biosurfactants should be crucial components for the future modern agriculture, since producing food requires a significant quantity of energy, and the technological processes generate a sizable amount of waste. The potential to connect agro-industrial ecosystems and use environmentally friendly processes would result in a bio-based circular economy for biosurfactant production. Nonetheless, in order to achieve such a desirable state, future research should tackle these renewable substrates and processes. To enhance current processes and meet the needs of industrial production systems, improved experimental setups can be developed [35,81].

6.2. Limitations

Due to its qualitative nature, this review presents a series of limitations. Although the study selection procedure was documented to assure reproducibility and transparency, the researcher bias can always affect how studies are categorized. The inclusion and exclusion criteria were outlined in the study in order to address this issue. Another limitation might be the decision to exclusively examine journal publications, which excludes the gray literature that could have brought additional insights. Additionally, it is possible that the literature evaluation we completed omitted a number of papers, case studies, or exploratory studies that are relevant to the research's goals. Such a limitation could be caused by the construction of the database query, as we selected publications based on the literal use of the concepts circular economy and provided only two alternative terms (sustainability and green economy).

7. Conclusions

The goal of this review was to identify and analyze biosurfactant contributions to the implementation of the circular economy, as well as to establish future research areas for better biosurfactant integration in the circular economy circuit. From a theoretical approach, this paper updated the role of biosurfactants in the transition to a circular economy. In terms of practical implications, the current findings provide insights for industrial entities dealing with waste processing, particularly organic waste, as bio-surfactants can be used to achieve organizational or national-level sustainability or circular economy goals.

The widespread application of biosurfactants stimulates research that makes use of these molecules on various technological fronts. A wide range of environmental activities, including the oil industry for the recovery of oils and the bioremediation of ecosystems, can use biosurfactants in order to shift towards a circular economy. Nevertheless, in order to broaden the industrial applicability of biosurfactants in the waste management sector, feasibility studies to determine if waste streams or industrial by-products are viable substrates for biosurfactant production must be conducted in the coming years. As a result, the production of biosurfactants can become economically viable through the use of low-cost substrates, the conception of ideal production conditions for various bioproducts, the development of new purification techniques, and the consolidation of high-yield strains. Pursuing purified products for high-value niche markets may also be a step towards achieving a circular economy [40,82]. To conclude, we affirm that biosurfactants present the potential for improving management alternatives for protecting and conserving our renewable and natural resources. The sample of papers analyzed revealed a synergic relationship between the circular economy and biosurfactants, such that the growing use of biosurfactants this will safeguard the diversity of different ecosystems, as well as the water supply, soil fertility, and pollution levels.

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Data Availability Statement: Not applicable.

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

Appendix A

Table A1. Final sample of papers included in the review.

No.	Authors	Article Title	Source Title	Key Words	Publication Year
1	Ambaye, TG; Formicola, F; Sbaffoni, S; Franzetti, A; Vaccari, M	Insights into rhamnolipid amendment towards enhancing microbial electrochemical treatment of petroleum hydrocarbon contaminated soil	Chemosphere	Biosurfactants; Bioelectrochemical system; Circular economy; Illumina; Remediation; Current density	2022
2	Zhang, Y; Placek, TL; Jahan, R; Alexandridis, P; Tsianou, M	Rhamnolipid Micellization and Adsorption Properties	International journal of molecular sciences	biosurfactant; green surfactant; rhamnolipid; self-assembly; formulation; bioremediation; sustainability	2022
3	Kee, SH; Ganeson, K; Rashid, NFM; Yatim, AFM; Vigneswari, S; Amirul, AA; Ramakrishna, S; Bhubalan, K	A review on biorefining of palm oil and sugar cane agro-industrial residues by bacteria into commercially viable bioplastics and biosurfactants	Fuel	Polyhydroxyalkanoates; Biosurfactant; Palm oil; Agro-industrial waste; Circular economy; Sugar cane	2022

Table A1. *Cont.*

No.	Authors	Article Title	Source Title	Key Words	Publication Year
4	Hollenbach, R; Delavault, A; Gebhardt, L; Soergel, H; Muhle-Goll, C; Ochsenreither, K; Syldatk, C	Lipase-Mediated Mechanoenzymatic Synthesis of Sugar Esters in Dissolved Unconventional and Neat Reaction Systems	Acs sustainable chemistry and engineering	biocatalysis; solvent-free; transesterification; glycolipid; lipase; biosurfactants	2022
5	Martinez, M; Rodriguez, A; Gea, T; Font, X	A Simplified Techno-Economic Analysis for Sophorolipid Production in a Solid-State Fermentation Process	Energies	solid-state fermentation; sophorolipids; waste; biosurfactant; techno-economic analysis	2022
6	Kachrimanidou, V; Alimpoumpa, D; Papadaki, A; Lappa, I; Alexopoulos, K; Kopsahelis, N	Cheese whey utilization for biosurfactant production: evaluation of bioprocessing strategies using novel *Lactobacillus* strains	Biomass conversion and biorefinery	Biosurfactants; *Lactobacilli*; Cheese-whey; Bioprocessing strategies; Bioreactors	2022
7	Sarubbo, LA; Silva, MDC; Durval, IJB; Bezerra, KGO; Ribeiro, BG; Silva, IA; Twigg, MS; Banat, IM	Biosurfactants: Production, properties, applications, trends, and general perspectives	Biochemical engineering journal	Biosurfactant; Microorganisms; Environmental sustainability; Green technology; Industrial applications	2022
8	Abd El-Malek, F; Rofeal, M; Zabed, HM; Nizami, AS; Rehan, M; Qi, XH	Microorganism-mediated algal biomass processing for clean products manufacturing: Current status, challenges, and future outlook	Fuel	Algal biomass; Microbial fermentation; Sustainability; Value-added products; Biorefinery	2022
9	Khodavirdipour, A; Chamanrokh, P; Alikhani, MY; Alikhani, MS	Potential of *Bacillus subtilis* Against SARS-CoV-2-A Sustainable Drug Development Perspective	Frontiers in microbiology	*Bacillus subitilis*; biosurfactant; COVID-19; drug development; surfactin	2022
10	Sharma, P; Gaur, VK; Gupta, S; Varjani, S; Pandey, A; Gnansounou, E; You, SM; Ngo, HH; Wong, JWC	Trends in mitigation of industrial waste: Global health hazards, environmental implications, and waste-derived economy for environmental sustainability	Science of the total environment	Environmental sustainability; Waste-derived economy; Bioplastic; Biosurfactants; Organic waste	2022
11	Duquet, F; Nada, AA; Rivallin, M; Rouessac, F; Villeneuve-Faure, C; Roualdes, S	Influence of Bio-Based Surfactants on TiO2 Thin Films as Photoanodes for Electro-Photocatalysis	Catalysts	TiO2 thin film; bio-based surfactant; electro-photocatalysis; hydrogen	2021
12	Kachrimanidou, V; Papadaki, A; Lappa, I; Papastergiou, S; Kleisiari, D; Kopsahelis, N	Biosurfactant Production from Lactobacilli: an Insight on the Interpretation of Prevailing Assessment Methods	Applied biochemistry and biotechnology	Biosurfactants; *Lactobacilli*; Surface tension; Cheese-whey; Screening	2022

Table A1. *Cont.*

No.	Authors	Article Title	Source Title	Key Words	Publication Year
13	Hu, XM; Subramanian, K; Wang, HM; Roelants, SLKW; Soetaert, W; Kaur, G; Lin, CSK; Chopra, SS	Bioconversion of Food Waste to produce Industrial-scale Sophorolipid Syrup and Crystals: dynamic Life Cycle Assessment (dLCA) of Emerging Biotechnologies	Bioresource technology	Life Cycle Assessment; Sustainable Processes; Waste Valorization; Biosurfactants; Sophorolipids	2021
14	Vieira, IMM; Santos, BLP; Ruzene, DS; Silva, DP	An overview of current research and developments in biosurfactants	Journal of industrial and engineering chemistry	Biosurfactant; Surfactant; Microorganism; Sustainability	2021
15	Janek, T; Gudina, EJ; Polomska, X; Biniarz, P; Jama, D; Rodrigues, LR; Rymowicz, W; Lazar, Z	Sustainable Surfactin Production by *Bacillus subtilis* Using Crude Glycerol from Different Wastes	Molecules	*Bacillus subtilis*; biosurfactant; surfactin; lipopeptides; industrial wastes; crude glycerol	2021
16	Sonnabend, M; Aubin, SG; Schmidt, AM; Leimenstoll, MC	Sophorolipid-Based Oligomers as Polyol Components for Polyurethane Systems	Polymers	polyurethane; polyol; bio-based; sophorolipid-based polyols; hydroxyl fatty acid-based polyols; platform chemicals	2021
17	Castelein, M; Verbruggen, F; Van Renterghem, L; Spooren, J; Yurramendi, L; Du Laing, G; Boon, N; Soetaert, W; Hennebel, T; Roelants, S; Williamson, AJ	Bioleaching of metals from secondary materials using glycolipid biosurfactants	Minerals engineering	Sophorolipids; Bioleaching; Heavy metal recovery; Fayalite; Copper	2021
18	Hu, XM; Subramanian, K; Wang, HM; Roelants, SLKW; To, MH; Soetaert, W; Kaur, G; Lin, CSK; Chopra, SS	Guiding environmental sustainability of emerging bioconversion technology for waste-derived sophorolipid production by adopting a dynamic life cycle assessment (dLCA) approach	Environmental pollution	Sophorolipids; Biosurfactants; Life cycle assessment; Dynamic life cycle assessment; Feedstock optimization; In-situ separation	2021
19	Chebbi, A; Franzetti, A; Castro, FD; Tovar, FHG; Tazzari, M; Sbaffoni, S; Vaccari, M	Potentials of Winery and Olive Oil Residues for the Production of Rhamnolipids and Other Biosurfactants: A Step Towards Achieving a Circular Economy Model	Waste and biomass valorization	Winery wastes; Olive oil wastes; Circular economy; Rhamnolipids; Biosurfactants; Agricultural wastes	2021
20	Martinez-Arcos, A; Moldes, AB; Vecino, X	Adding value to secondary streams of corn wet milling industry	Cyta-journal of food	Corn stream; nutritional supplement; biosurfactants; circular economy	2021

Table A1. *Cont.*

No.	Authors	Article Title	Source Title	Key Words	Publication Year
21	Drakontis, CE; Amin, S	Design of sustainable lip gloss formulation with biosurfactants and silica particles	International journal of cosmetic science	sustainability; lip gloss; rheometer; Aerosil; silica particles; biosurfactants; rhamnolipids; sophorolipids; silicone oil; cosmetic formulation	2020
22	Singh, R; Glick, BR; Rathore, D	Role of textile effluent fertilization with biosurfactant to sustain soil quality and nutrient availability	Journal of environmental management	Textile effluent; Biosurfactant; Soil health; Triticum aestivum; Capsicum annum	2020
23	Hruzova, K; Patel, A; Masak, J; Matatkova, O; Rova, U; Christakopoulos, P; Matsakas, L	A novel approach for the production of green biosurfactant from *Pseudomonas aeruginosa* using renewable forest biomass	Science of the total environment	Rhamnolipid; Biosurfactants; *Pseudomonas*; Wood hydrolysate; Organosolv fractionation	2020
24	Sadhukhan, J; Dugmore, TIJ; Matharu, A; Martinez-Hernandez, E; Aburto, J; R26ahman, PKSM; Lynch, J	Perspectives on Game Changer Global Challenges for Sustainable 21st Century: Plant-Based Diet, Unavoidable Food Waste Biorefining, and Circular Economy	Sustainability	biorefinery and bioeconomy; food waste and circular economy; zero hunger zero poverty; sustainable food; food policy; vegan protein;	2020
25	Jimenez-Penalver, P; Koh, A; Gro28ss, R; Gea, T; Font, X	Biosurfactants from Waste: Structures and Interfacial Properties of Sophorolipids Produced from a Residual Oil Cake	Journal of surfactants and detergents	Biosurfactant; Critical micelle concentration; Emulsion; LC-MS; Sophorolipids; Waste	2020
26	Soare, M. G., Lakatos, E. S., Ene, N., Malo, N., Popa, O., and Babeanu, N.	The potential applications of *Bacillus* sp. And *Pseudomonas* sp. Strains with antimicrobial activity against phytopathogens, in waste oils and the bioremediation of hydrocarbons	Catalysts	antimicrobial activity; biosurfactants; emulsion index; sunflower oil; hydrocarbons	2019
27	Lu, Y; Zhu, YL; Xu, ZH; Liu, QX	Pseudo-Gemini Biosurfactants with CO2 Switchability for Enhanced Oil Recovery (EOR)	Tenside surfactants detergents	Biosurfactants; pseudo-gemini surfactants; CO2 switchable compounds; enhanced oil recovery (EOR); oil-water separation	2019
28	Etchegaray, A; Coutte, F; Chataigne, G; Bechet, M; dos Santos, RHZ; Leclere, V; Jacques, P	Production of *Bacillus amyloliquefaciens* OG and its metabolites in renewable media: valorization for biodiesel production and p-xylene decontamination	Canadian journal of microbiology	*Bacillus* sp.; sustainability; lipopeptides; biosurfactants; environmental decontamination; circular bioeconomy	2017

Table A1. *Cont.*

No.	Authors	Article Title	Source Title	Key Words	Publication Year
29	Franzetti, A; Gandolfi, I; Raimondi, C; Bestetti, G; Banat, IM; Smyth, TJ; Papacchini, M; Cavallo, M; Fracchia, L	Environmental fate, toxicity, characteristics, and potential applications of novel bioemulsifiers produced by Variovorax paradoxus 7bCT5	Bioresource technology	Biosurfactant; Bioemulsifiers; Crude oil; Environmental sustainability	2012
30	Dreja, M; Vockenroth, I; Plath, N	Biosurfactants-Exotic Specialties or Ready for Application?	Tenside surfactants detergents	Biosurfactants; Sustainability; Surface Tension; Wetting; Detergents	2012

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