

Review

Bioremediation Potential of Sunflower-Derived Biosurfactants: A Bibliometric Description

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Abstract: Biosurfactants are amphiphilic molecules capable of reducing the surface tension of water and forming emulsions between immiscible liquids. These versatile molecules find applications in different industrial sectors, standing out in environmental applications, such as the bioremediation agents of contaminated environments. Bioremediation is an emerging sustainable method of controlling the degradation of waste. The present study carried out a bibliometric analysis, reviewing all research published in the SCOPUS database up to 2023, focused on producing biosurfactants from sunflowers with applications in this sustainable method of waste degradation. Using sunflowers to produce biosurfactants proved an ecological, sustainable, and economical alternative to conventional substrates. The results showed that only the seed husks, the oil derived from the seed, and the sunflower stems were used to produce biosurfactants, emphasizing oil as the most used raw material, probably due to its rich linoleic acid content. The preliminary selection detected only 12 articles that addressed the subject under analysis. According to these studies, the tested biosurfactants showed high potential for application in sustainable environmental bioremediation processes and were able to decontaminate soil, water, and liquid effluents. The bibliometric analysis was performed with the VOSviewer software to evaluate the quality of the publications and, above all, to show a more comprehensive scenario of the subject based on the following bibliometric indicators: the most productive journals, publications by country, the most cited articles, the most recurrent keywords, and most productive institutions. These insights will undoubtedly help scientists to develop new and sustainable practices of waste degradation and contribute to bioremediation research using biosurfactants from sunflowers. By showcasing the environmental benefits and practicality of sunflower-derived biosurfactants, this study contributes to the broader discourse on sustainable bioremediation, fostering innovative and eco-friendly waste management solutions.

Keywords: biosurfactants; bioremediation; degradation; environment; sunflower; sustainability; waste



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1. Introduction

The large amount of organic waste generated by the oil, food, and agricultural industries reflects a worldwide health and environmental problem [1]. Several waste control and management actions can be adopted to mitigate this problem, including utilizing agro-industrial waste to produce biosurfactants [2]. In this context, the application of biotechnological techniques to use agro-food waste that would otherwise be discarded significantly reduces environmental pollution and, at the same time, allows the economical production of high-value-added bioproducts, including biosurfactants [3].

Science defines biosurfactants as amphiphilic molecules that can interact with aqueous and oily media simultaneously due to their complex structure composed of lipophilic (nonpolar) and hydrophilic (polar) parts. Thus, the nonpolar portion is formed by hydrocarbons, while the polar portion can be classified as anionic, cationic, or amphoteric [4]. These agents are divided into four main groups: glycolipids, lipopeptides, and lipoproteins; phospholipids; fatty acids; and polymeric biosurfactants [5]. The first three groups have a low molecular weight, whereas a high molecular weight characterizes the last group. From this perspective, those groups with a low molecular weight are more effective in reducing the surface and interfacial tension between two immiscible fluids, unlike those with a high molecular weight, which are more effective in forming emulsions between immiscible liquids [6].

Biosurfactants can be synthesized by several microorganisms that use a multitude of waste as a food source [7]. These microorganisms include bacteria, yeast, and fungi [8]. For optimal biosynthesis, the cultivation medium must supply the necessary nutrients, particularly carbohydrates and lipids as carbon sources, along with nitrogenous compounds as nitrogen sources to support efficient microbial metabolism [9]. This microbial synthesis occurs either by solid-state fermentation or liquid-state (submerged) fermentation [10].

Regarding ecology and functionality, biosurfactants have several advantages over synthetic surfactants due to their biodegradable nature, low toxicity, and ability to act as antimicrobial agents. They also present similar or better physicochemical properties in environmental applications [11]. Unlike synthetic surfactants, biosurfactants can be synthesized from sustainable and inexpensive substrates [12,13].

Despite all the advantageous characteristics listed, synthetic surfactants outperform biosurfactants in the commercial market [14]. This suggests that the adoption of biosurfactants in this field is still evolving, in contrast to chemical surfactants, which are already well-established in the market [15]. In this context, the use of biosurfactants in various industrial sectors is currently limited, mainly due to their low yields and high production costs. These factors make them difficult to use in large-scale applications, making them more expensive and less accessible. In contrast, synthetic surfactants are produced in large quantities and are cheaper and, therefore, more widely used. In Europe, the cost of a sophorolipid biosurfactant is estimated to range from EUR 20 to 30 per kilogram, compared to just EUR 1 per kilogram for a synthetic surfactant [16]. This highlights a significant gap between the prices of biosurfactants and their competitors. However, while the chemical surfactant market currently dominates, this dynamic could shift anytime in the future. This is possible because the global need for environmental preservation associated with a more sustainable society and changes in consumer behavior are leading several multimillion-dollar companies to invest in eco-friendly products that minimize environmental impact. In this regard, biosurfactants hold a significant advantage over chemical surfactants as they are environmentally friendly and derived from sustainable sources [15]. Thus, the trend is for biosurfactants to gain increasing attention and space on the global stage. However, many challenges still need to be overcome to achieve this scenario. For example, biosurfactants' low yields and high production costs significantly

reduce their competitiveness in the market, limiting their use. In this sense, the literature describes some measures that can be adopted to mitigate these impasses.

The biosurfactant yield can be increased by choosing the substrate and using selected microbial strains capable of metabolizing different types of waste [17]. Statistical tools can also optimize production parameters to obtain higher yields without increasing the number of experiments performed [18]. According to the literature, optimizing the operational conditions for cultivating microorganisms (temperature, pH, and aeration) and the composition of the cultivation medium tends to increase biosurfactant production [19]. In parallel, agro-industrial waste is an ecological, promising, and widely studied alternative with great potential to reduce the overall cost of biosurfactant production [20]. This type of raw material comes from the processing of other raw materials of plant origin (fruits, vegetables, oil, and plant stems) and animal origin (meat and milk) [21]. From this perspective, raw materials from sunflowers fulfill this role well since they are cheap, abundant, and renewable [22].

Sunflower (*Helianthus annuus* Linnaeus) is one of the main oilseed crops, offering various products and by-products of economic value [23]. Other products can be obtained by recycling the waste generated after harvesting the seeds. These components of waste include stems, leaves, flowers, and seed shells [24]. The oleaginous characteristic of the plant is associated with the rich oil content in its seeds. This oil, whether virgin or residual, is composed of several fatty acids, making it an important carbon source for biosurfactant production [25,26]. Considering several environmental problems caused by the inadequate disposal of residual frying oil, using residual sunflower oil becomes an ecological and economical alternative [27]. In addition, other sunflower residues, such as seed bran and stem, can also be used to produce biosurfactants, given the cellulose composition of these raw materials [28]. With this perspective, Santos et al. [22] extracted hemicellulose from sunflower stems and used this polysaccharide as a substrate to synthesize biosurfactants. On the other hand, El-Halmouch et al. [29] used sunflower seed husks as a substrate for the same purpose.

Biosurfactants demonstrate strong resistance to a wide range of temperatures, pH levels, and hypersalinity, making them highly effective for industrial and environmental applications due to their biodegradability and low toxicity [30,31]. They have a broad field of action, finding applications in different areas, such as oil [32], agriculture [33], medicine [34], food [35], cleaning products [36], and bioremediation agents for contaminated sites [37]. In this sense, bioremediation is a set of ecological actions that aim to reduce environmental contamination [38]. Several scientific studies have investigated the application of biosurfactants for this purpose. For example, Dasgupta et al. [39] observed that biosurfactants could act as chelating agents capable of neutralizing the action of heavy metals in aqueous media. Other studies have also observed that biosurfactants can favor the removal of hydrophobic pollutants in soil [40] and seawater [41,42]. Furthermore, these agents can also facilitate the removal of herbicides from soil particles [43], increase the solubilization and consequently the bioavailability of different types of pesticides in water [44,45], promote the biodegradation of hazardous aromatic amines [46], as well as favor the degradation of polychlorinated pollutants [47].

Considering the information presented, this study aims to provide a comprehensive overview of the research on biosurfactant production from sunflowers, with a particular focus on bioremediation applications. The findings are intended to support and inspire the scientific community in advancing new research in this field. To achieve these objectives, a bibliometric review was performed considering all articles related to the topic from the Scopus database and published until 2023.

2. Materials and Methods

The search and collection of scientific articles was performed in the SCOPUS database, as it is one of the largest and most comprehensive databases of scientific documents [48]. However, a search query was previously constructed through a strategic combination of keywords governed by Boolean operators to capture all prefixes and suffixes of the different words, and quotation marks were used to capture terms composed of more than one word.

On the SCOPUS platform, the option to search for articles by titles, abstracts, and keywords simultaneously was selected. Initially, a query was created containing the term “bioremediation” and other terms related to “sunflower” and “biosurfactants”. According to the search results, an insufficient number of articles were generated. This may be associated with a limitation from using the term “bioremediation” once some articles were not generated in the results due to the absence of this term in their titles, abstracts, and keywords. Despite this absence, these articles addressed bioremediation in their results and discussion sections. Therefore, the term “bioremediation” was removed from the query to avoid losing data. Consequently, to analyze which articles addressed bioremediation, it was necessary to study the results and discussion sections of all articles generated in the search.

Regarding the source of raw material used to produce biosurfactants, the sunflower was chosen because it stands out as offering a variety of valuable raw materials for this purpose, including seed shells [49], residual frying oil derived from seeds [50], and stalks [22]. Given this information, the following search query was created: TITLE-ABS-KEY ((“sun flower*” OR “sun-flower*” OR sunflower* OR Helianthus OR “H. annuus” OR annuus OR Heliantus OR annus OR anuus) AND (*surfactant* OR *emulsifi* OR *tensoactive* OR surface-activ* OR *tensioactive* OR “surface activ*” OR “hidrophobic organic*” OR “surface tens*” OR amphiphilic* OR “bio-surfactant*” OR *floculant* OR bio-floculant*)) AND (LIMIT-TO (DOCTYPE, “ar”)).

Through searches using this query, 1498 articles published up to 2023 were generated. All these articles were gathered and exported from SCOPUS utilizing a spreadsheet. Through an initial analysis, it was possible to identify and disregard all articles that did not fit the research theme. This group included all articles that did not address the production of biosurfactants from sunflowers. As a result, 113 articles were selected for further evaluation, and the others were excluded. In this context, to choose the articles that addressed the theme, a more rigorous analysis of the 113 articles was carried out, resulting in only 12 articles that discussed the production of biosurfactants from sunflowers with applications in bioremediation. These articles were gathered and exported from SCOPUS in spreadsheet format to be subjected to bibliometric analysis using the VOSviewer (version 1.6.20) software, which is a handy statistical tool for constructing, exploring, and visualizing bibliometric network maps. Through using this tool, it is possible to analyze many publications at once, visualizing their relationships in network maps. These maps can be generated from the combination of the following information from the analyzed articles: authors, journals, keywords, citations, countries, and institutions [51].

3. Results and Discussion

3.1. Overview of Articles

As previously discussed, the search conducted in the Scopus database resulted in 1498 articles associated with 27 different areas of academic research. The areas of chemistry, agricultural and biological sciences, and chemical engineering stood out with 623, 611, and 536 articles, respectively. The percentage contribution of each area is presented in Figure 1.

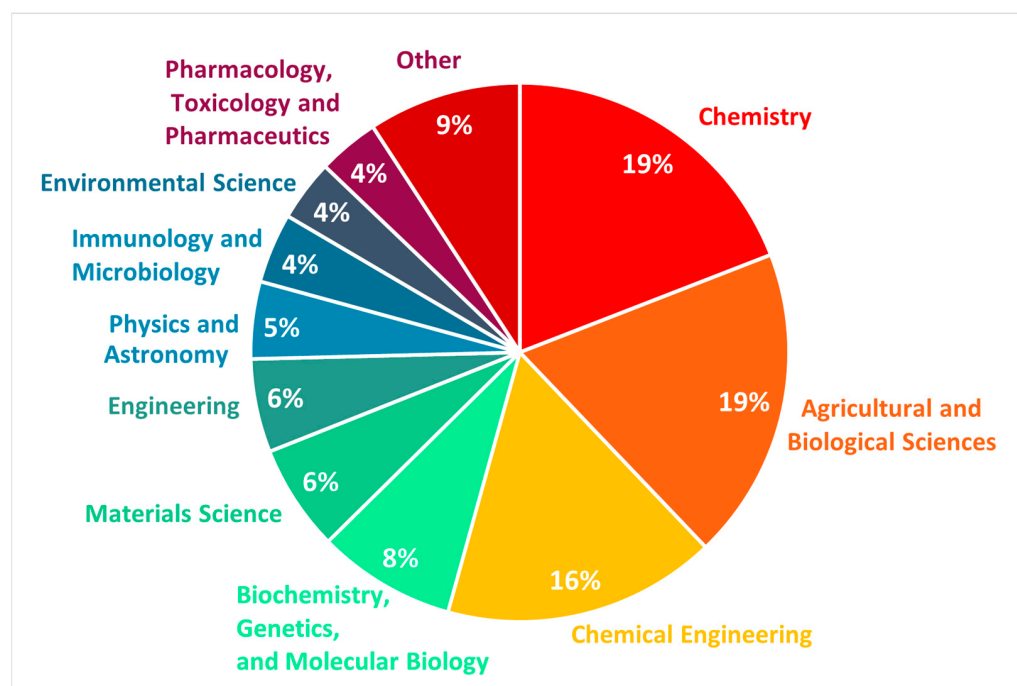


Figure 1. Percentage contribution of the different research areas of the articles found in the SCOPUS database.

A thorough analysis of the 113 articles that progressed to the subsequent evaluation stages made it possible to note that most of them did not address the production of biosurfactants from sunflowers with applications in bioremediation. However, several studies that evaluated biosurfactants' production from various raw materials from sunflowers were explored, focusing on different biosurfactant applications. For example, Jadhav et al. [52] produced a biosurfactant from sunflower seed cake with other residues and investigated its inhibitory activity against the fungi *Aspergillus niger* and *Penicillium chrysogenum*. On the other hand, Pirog et al. [53] investigated the effectiveness of a biosurfactant derived from residual sunflower oil in disrupting biofilms of pathogenic microorganisms formed on silicone tubes commonly used in the medical field. Ciurko et al. [34] synthesized a lipopeptide biosurfactant (surfactin) from sunflower oil cake and investigated its role in inhibiting the angiotensin-converting enzyme that causes high blood pressure. Rashad et al. [54] produced a sophorolipid biosurfactant in a mixture of sunflower oil cake and soybean oil to study its anticancer activity by inhibiting various types of cancer cells. Hazra, Kundu, and Chaudhari [33] investigated the insecticidal activities of a lipopeptide biosurfactant produced by *Bacillus clausii* BS02 from sunflower oil soap stock against agricultural pests (the pulse beetle and mealybug). Finally, Amani [32] synthesized a rhamnolipid biosurfactant from sunflower oil, testing its efficiency in removing oil from glass micromodels and simulating oil removal from porous rocks of oil reservoirs.

Additional studies were identified exploring the effects of sunflower oil and liquor from sunflower stalks on biosurfactant production. Pirog et al. [55] tested the quality of different residual sunflower oils to verify the highest yields in biosurfactant synthesis. Hamed, Al-Wasify, and Ragab [26] separately used four types of vegetable oil and observed that sunflower oil favored the yield of biosurfactants more due to its high linoleic acid content (60%). Ferraz, De Araújo, and Pastore [56] observed the greater effectiveness of linoleic acid in increasing biosurfactant production than some oils. Ianieva [57] observed a five-fold increase in the yield of biosurfactant production due to the addition of sunflower oil to the culture medium. Hajfarajollah, Mokhtarani, and Noghabi [58] reported a higher biosurfactant production (almost five times higher) in the medium containing sunflower

oil than in the medium containing glucose. Vollbrechta et al. [59] tested different lipophilic substrates such as glucose, glycerol, and others during the synthesis of biosurfactants and observed that sunflower oil provided higher product yields (4–5 g/L). Langer et al. [60] observed the greater prominence of sunflower oil in the yield of biosurfactants (22.5 g/L) compared to rapeseed and marigold oils. Bezza and Chirwa [61] compared the influence between sunflower oil and glycerol and concluded that sunflower oil promoted a ten times higher yield and better physicochemical properties of biosurfactants. Pantasaki et al. [62] observed a higher (300 mg/L) and faster (40 h) biosurfactant production for sunflower oil compared to oleic acid, which showed a yield of 250 mg/L in 60 h. Finally, Santos et al. [22] evaluated the potential of hemicellulosic liquor derived from sunflower stalks as a partial substitute for glucose, observing a higher surface tension reduction (58.68%) and cell concentration (4.56 g/L) for the biosurfactant produced using the liquor.

Studies were also found concerning the simultaneous production of biosurfactants with other products. For example, Wei and Chen [63] synthesized prodigiosin, which is a red pigment, using *Serratia marcescens* SMR cultivated in media supplemented with sunflower, olive, and soybean oils. The authors observed that the concurrent production of a biosurfactant enhanced the synthesis process. Jakovetic et al. [64] compared the production processes of a rhamnolipid biosurfactant and the lipase enzyme, both synthesized by *Pseudomonas aeruginosa* strain cultivated in sunflower oil-based media. Velioglu and Urek [65] investigated the production of a biosurfactant using *Pleurotus djamor* fungi cultivated on sunflower seed shells combined with other residues, noting the simultaneous synthesis of the lipase enzyme. In a different work, Velioglu and Urek [66] investigated the simultaneous production of biosurfactants and three ligninolytic enzymes (laccase, manganese peroxidase, and lignin peroxidase) from *Pleurotus* spp. grown on sunflower seed shells.

3.2. Biosurfactant Production from Sunflowers

Among the 113 papers, 12 original scientific articles on producing biosurfactants from sunflowers with applications in bioremediation were identified, as shown in Table 1. These articles were distributed across 12 academic areas, emphasizing chemistry, agricultural and biological sciences, chemical engineering, and biochemistry, and genetics and molecular biology (Table 2).

Table 1. Articles selected from the Scopus database.

Authors	Applications in Bioremediation
França et al. [67]	Removal of hydrocarbons and heavy metals from soils and effluents
Jimoh and Lin [68]	Removal of motor oil and diesel from sand
Velioglu and Urek [69]	Removal of residual frying oil from beach sand
Bezza and Chirwa [70]	Removal of oil from sand
Xia et al. [71]	Removal of oil from sand
Rashad et al. [72]	Removal of oil from sand
Minucelli et al. [73]	Biodegradation of oil from soil
Samadi et al. [74]	Removal of oil from seawater
Elkhouly et al. [75]	Remediation of the aqueous solution of heavy metals
Jayalatha and Devatha [76]	Biodegradation of Triclosan in domestic effluents
Jayalatha and Devatha [77]	Biodegradation of Triclosan and Ibuprofen in domestic effluents
Sonde and Di Vakaran [78]	Precipitation of lead in effluents

Table 2. The number of scientific articles published according to different research areas.

Research Area	Publication Number	Percentage (%)
Chemical Engineering	5	20
Environmental Science	4	16
Biochemistry, Genetics and Molecular Biology	3	12
Chemistry	3	12
Immunology and Microbiology	2	8
Energy	2	8
Agricultural and Biological Sciences	1	4
Pharmacology, Toxicology and Pharmaceuticals	1	4
Materials Sciences	1	4
Medicine	1	4
Earth and Planetary Sciences	1	4
Engineering	1	4

Table 2 describes the number of scientific articles per academic area and each area's contribution percentage, with some publications simultaneously belonging to more than one area of knowledge. Several areas of knowledge may be associated with biosurfactants, which are the focus of various studies. For example, the work of França et al. [67] falls within the field of chemical engineering, as it focuses on the kinetics of biosurfactant production by analyzing substrate consumption by bacterial cells over the fermentation period. In contrast, Jimoh and Lin [68] examined the use of biosurfactants for soil and water decontamination from various hydrophobic pollutants, positioning their research within the environmental science domain. In the area of biochemistry, genetics, and molecular biology, Velioglu and Urek [69] explored the biochemical composition of a biosurfactant using chromatography and mass spectrometry techniques.

A detailed analysis of the 12 articles selected identified some common conditions. The three main conditions were sunflower substrates, the microorganisms used, and the type of fermentation employed.

3.2.1. Sunflower Substrates

The substrate serves as the primary nutrient source for microorganisms, enabling them to produce biosurfactants efficiently. In this sense, it was observed that only oil and seed husk residues were selected for biosurfactant production among the sunflower-derived materials. The simultaneous use of husks and oil was reported only in the research published by Velioglu and Urek [69]. In other studies, different forms of sunflower oil (residual frying oil and commercial oil) were used either as the sole carbon source [67,68,70,71,74–78] or in combination with other substrates [69,72,73]. In this context, it is important to highlight that although some works used commercial and non-residual oil as raw material, the results showed that commercial oil is useful for producing biosurfactants despite not being the cheapest raw material [73,74]. Thus, different types of sunflower oil are equally valuable to produce biosurfactants, given the similarities between them. As observed by Wang et al. [50], although the yield in biosurfactant production was slightly higher for commercial oil, the biosurfactant produced by both oils had similar chemical structures. In addition, the authors reported that frying oil requires a lower cost than commercial oil, helping to reduce the environmental contamination caused by improper waste oil disposal. Taking into account all studies that utilized sunflower oil as a raw material, this preference is likely driven by sustainability factors, such as the proper disposal of waste oil, along with the demonstrated ability of sunflower oil to enhance biosurfactant production yields, as

highlighted in Section 3.1 [26,56–62]. At the same time, the use of sunflowers can generate biosurfactants with better physicochemical properties. For example, using residual sunflower oil, Sonde and Di Vakaran [78] produced a biosurfactant with better precipitation properties of lead in effluents. Furthermore, the substrate can also influence the biochemical composition of the molecular structure of biosurfactants. This is because the source of nutrients, such as carbon, directly affects microbial metabolism, generating products with specific characteristics. In this context, hydrophobic substrates from sunflower oil can induce the addition of fatty acids in biosynthetic pathways, generating biosurfactants with a chemical structure containing lipid moieties [25,62]. In addition, abundance, easy acquisition, and low cost may have been considered when choosing the raw material.

3.2.2. Selected Microorganisms

Microorganisms are biosurfactant-producing agents. The choice of microorganisms to produce biosurfactants is important since this choice influences the type of biosurfactant produced. Thus, Table 3 shows all the microorganisms used in the 12 studies and their respective biosurfactants.

Table 3. Selected microorganisms and their respective biosurfactants.

Microorganisms	Biosurfactant Type	References
<i>Bacillus subtilis</i> ICA56 *	Lipopeptide	França et al. [67]
<i>Bacillus licheniformis</i> *	Lipopeptide	Jayalatha and Devatha [76]
<i>Paenibacillus</i> sp. D9 *	Lipopeptide	Jimoh and Lin [68]
<i>Pseudomonas aeruginosa</i> CB1 and <i>Bacillus subtilis</i> CN1 *	—	Bezza and Chirwa [70]
<i>Pseudomonas aeruginosa</i> *	Rhamnolipid (glycolipid)	Xia et al. [71]
<i>Pseudomonas aeruginosa</i> PTCC 1340 *	Rhamnolipid (glycolipid)	Samadi et al. [74]
<i>Pseudomonas aeruginosa</i> MTCC 1688 *	Rhamnolipid (glycolipid)	Jayalatha and Devatha [77]
<i>Pseudomonas aeruginosa</i> *	Rhamnolipid (glycolipid)	Elkhouly et al. [75]
<i>Pseudomonas Putida</i> ¹	—	Sonde and Di Vakaran [78]
<i>Candida bombicola</i> NRRL Y-17069 **	Sophorolipid (glycolipid)	Rashad et al. [72]
<i>Candida bombicola</i> ATCC 22214 **	Sophorolipid (glycolipid)	Minucelli et al. [73]
<i>Pleurotus djamor</i> ***	—	Velioglu and Urek [69]

* Bacteria; ** yeast; *** filamentous fungus.

Santos et al. [15] gathered several species of microorganisms typically used to produce biosurfactants. In this sense, each species can synthesize one or more specific types of these biocompounds. Thus, lipopeptide biosurfactants were found to be produced by the following bacteria: *Bacillus subtilis*, *Bacillus pumilus*, *Bacillus megaterium*, *Bacillus amyloliquefaciens*, *Bacillus licheniformis*, *Serratia marcescens*, and *Pseudomonas fluorescens*. Glycolipids are produced by other bacteria, such as *Pseudomonas aeruginosa*, *Rhodococcus* sp., and *Gordonia* sp., in addition to the fungi *Ustilago maydis* and *Pseudozyma churashimaensis* and the yeast *Starmerella bombicola* (*Candida bombicola*). The authors also identified that the bacterium *Corynebacterium insidibasseosum* produces phospholipids. At the same time, polymeric biosurfactants can be synthesized by the bacteria *Acinetobacter calcoaceticus*, *Acinetobacter lwoffii*, and *Acinetobacter radioresistense* and by yeast such as *Yarrowia lipolytica*. Finally, particulate biosurfactants from *Acinetobacter calcoaceticus* and *Serratia marcescens* were also listed.

3.2.3. Fermentation Type

Biosurfactant production can occur through two distinct fermentation processes: solid-state fermentation or submerged fermentation. Comparing these two types of fermentation, Colla et al. [79] highlighted that solid-state fermentation is distinguished using cost-effective solid substrates, simple equipment, low-energy requirements, minimal moisture, and

higher product concentrations. In contrast, submerged fermentation offers advantages such as greater medium homogeneity and easier control of process parameters like temperature and pH. The authors also noted that submerged fermentation is the most well-known and widely adopted method globally. Considering solid-state fermentation, Das and Murkherjee [80] also reported that the process requires less water, so less effort is required in the biosurfactant extraction and purification steps and when managing the generated effluent. Therefore, the choice of the fermentation process involves many factors. In the select articles, Velioglu and Urek [69] produced biosurfactants by solid-state fermentation, while Rashad et al. [72] used both solid-state and liquid-state fermentation (submerged fermentation). The other works used submerged fermentation for biosurfactant synthesis.

3.3. Bioremediation Applications

After synthesizing different types of biosurfactants from sunflowers, which was the theme of this work, the authors performed several applications, including bioremediation. Thus, the 12 articles were grouped according to the bioremediation tests performed on soil, water, and liquid effluents. Only Jimoh and Lin [68] addressed simultaneous bioremediation in soil and water, while França et al. [67] evaluated bioremediation in soil and liquid effluent.

3.3.1. Bioremediation in Soil Samples

Focusing on the bioremediation of soils contaminated by different hydrophobic pollutants, França et al. [67] synthesized a lipopeptide biosurfactant from *Bacillus subtilis* ICA56 grown on residual sunflower oil to investigate its potential for removing crude oil and engine oil from sand. The authors added 250 mg/L of the crude biosurfactant (microbial cell-free supernatant) to 20 g sand samples contaminated with 2 g of crude oil. The samples were incubated in an orbital shaker (27 °C, 150 rpm, 24 h) and centrifuged. Dichloromethane was used as the chemical solvent for oil extraction, and the oil mass was obtained using gravimetric techniques. For comparative purposes, the authors repeated the same procedure for synthetic surfactants and the fermented broth from the biosurfactant production. The results showed that the fermented broth exhibited a higher oil removal efficiency than the crude biosurfactant and synthetic surfactants, reaching 85% for crude oil and 90.8% for motor oil. This indicates that the biosurfactant offered more efficient bioremediation than the synthetic surfactants, demonstrating that this efficiency is not necessarily linked to their purity, as the fermented broth—a residual mixture of the biosurfactant and other substances—showed a higher performance. It is also important to highlight that the authors applied the crude biosurfactant at a concentration above its critical micelle concentration (CMC). Under these conditions, as Chaprão et al. [81] described, oil solubilization occurs above the biosurfactant's CMC. The oil's apparent solubility significantly increases due to its aggregation into the biosurfactant micelles, which facilitates its removal from the sand.

Using waste sunflower oil as a carbon source, Jimoh e Lin [68] produced a lipopeptide biosurfactant and evaluated its bioremediation potential for various pollutants, following the same strategy as França et al. [67]. The removal of different oils in sand was evaluated under shaking and static conditions. During the tests, the authors added 40 mL of the crude biosurfactant (500 mg/L) to 50 g of sand contaminated with 10% diesel or motor oil. These samples were incubated for bioremediation tests. This procedure was repeated for the synthetic surfactant and cell-free fermentation broth. The results indicated that the shaking conditions (30 °C, 150 rpm, 48 h) were more favorable for removing contaminants. The crude biosurfactant performed better than the synthetic surfactants in both tested conditions. However, the fermented broth showed the highest removal percentage, achieving 76.3% for the sample contaminated with motor oil and 74.4% for diesel oil under shaking

conditions. Therefore, as Chaprão et al. [81] reported, the cell-free broth is an effective and economical alternative for removing pollutants from the soil because it does not require purification steps before its application, significantly reducing any associated costs.

Velioglu and Urek [69] also obtained satisfactory results in bioremediation applications. They used a white rot fungus (*Pleurotus djamor*) to produce a biosurfactant in solid-state fermentation in media containing sunflower seed shells. The authors evaluated the biosurfactant's performance in removing waste frying oil from beach sand. During the evaluation, a solution of the crude biosurfactant (1000 mg/L) was added to samples containing 25 g of sand contaminated by 5 mL of oil. These samples were incubated in an orbital shaker (25 °C, 150 rpm, 24 h) and centrifuged, obtaining the mass of oil removed using the same strategies previously described. The results demonstrated that biosurfactants removed 76.57% of oil from the sand.

Bezza and Chirwa [70] used sunflower oil as a substrate to produce biosurfactants and adopted the same oil removal technique as Velioglu and Urek [69] but investigated the process under higher biosurfactant concentrations. In this case, 60 g of sand was contaminated with 5 mL of oil, and 20 g fractions of sand were used for the bioremediation tests. Two solutions of the crude biosurfactant were separately introduced at concentrations above CMC into the sand samples. The results showed an oil recovery of 88% at a concentration of 900 mg/L and 67% at 1800 mg/L, suggesting that the efficiency of these agents in removing pollutants is not necessarily related to high concentrations. This was confirmed by Chaprão et al. [81], who affirmed that despite the biosurfactant concentration being an important factor for removing hydrophobic pollutants from soil, the removal efficiency did not necessarily improve by significantly increasing the concentration levels.

In another approach, following a method of oil recovery using the core flooding system, Xia et al. [71] produced a rhamnolipid biosurfactant from *Pseudomonas aeruginosa* WJ-1 grown on waste sunflower oil, investigating its potential to remove crude oil from sand. In the procedure, sand pack columns were contaminated with oil. Initially, 50–52% of the original sample remained unrecovered in the column. Brine flooding (initial water flooding) was ineffective in extracting this residual oil. Both bacterium and biosurfactant flooding (secondary water flooding) were subsequently applied as a tertiary oil recovery method to retrieve the trapped oil, resulting in an additional recovery of 9.02% and 23.02%, respectively. Although the authors did not mention the phenomena involved in the bioremediation tests, removing oily pollutants by biosurfactants and bacteria generally occurs through solubilization and biodegradation mechanisms.

Rashad et al. [72] reached a similar conclusion by assessing the effectiveness of kerosene removal by two sophorolipid biosurfactants produced via solid-state fermentation using a mixture of sunflower oil cake and motor oil waste as a substrate. During the tests, they saturated sand columns (100 g) with 100 mL of oil and flooded them with 100 mL of a biosurfactant solution at 1 mg/mL (a concentration lower than CMC). The results showed that both biosurfactants effectively removed oil, achieving removal efficiencies of 71.43% (for the methanol-extracted biosurfactant) and 72.73% (for the ethyl acetate-extracted biosurfactant). At concentrations below the CMC, Chaprão et al. [81] reported that in oil–soil systems, a mobilization phenomenon occurs, wherein the biosurfactant reduces the interfacial force that keeps the oil attached to the soil particles, facilitating its removal.

Unlike all these studies, Minucelli et al. [73] investigated the potential of a sophorolipid biosurfactant produced from commercial sunflower oil to aid in the biodegradation of oil in soil by measuring gaseous CO₂. During the investigation, the authors used two approaches: sophorolipids and a commercial consortium of microorganisms (Enzilimp) to treat 100 g samples of sandy soil contaminated with 5% commercial lubricant oil. Every

24 h, the rate of CO₂ release from oil degradation was measured. The results showed that a lower biosurfactant concentration (1 g/kg soil) was necessary to increase the solubility of the hydrophobic compound with the microbial solution, favoring more significant oil degradation. The maximum intensity of this phenomenon was observed by the highest release of CO₂ (approximately 27 µg) that occurred after 4 days of incubation.

Other reports in the literature have confirmed the effectiveness of biosurfactants in aiding in the microbial biodegradation of hydrophobic pollutants in soils. In this context, Decesaro et al. [82] demonstrated that the lipopeptide biosurfactant (0.5% w/w) synthesized from whey-based culture medium supplemented with soybean oil favored the microbial biodegradation of oil in clay soil, resulting in a higher release of CO₂ (6474.41 mg C_{CO2}/kg of soil) after an incubation period of 90 days. The authors highlighted that the biosurfactant enhanced the oil's solubility in the aqueous phase, increasing its bioavailability as a nutrient source for soil microorganisms. As a result, 57.25% of the pollutant was degraded, leading to a higher microbial release of CO₂.

3.3.2. Bioremediation in Water Samples

To evaluate the potential of a rhamnolipid biosurfactant produced in commercial sunflower oil, Samadi et al. [74] added a biosurfactant solution at different concentrations (0.1–0.7 g/L) to Petri dishes containing seawater contaminated with crude oil. The authors noted a significant displacement of the oil film over the water so that the diameter of the clarified region increased from 0 to 9 cm, indicating an almost complete reduction in the area contaminated by oil. The study highlighted that this phenomenon may be associated with the ability of the biosurfactant to interact with the aqueous and oily phases simultaneously, thus reducing the contact angle between the water and oil molecules.

Furthermore, biosurfactants may exhibit good tolerance and stability in marine environments with high salt concentrations. Syahriansyah and Hamazah [83] observed this when they produced a biosurfactant using mineral salt supplemented with sunflower oil.

In the field of the bioremediation of aqueous environments contaminated by heavy metals, Elkhoully et al. [75] synthesized a rhamnolipid biosurfactant in residual sunflower oil. They investigated its influence on reducing the concentration of five heavy metals: Ag₂SO₄, FeCl₃, CoCl₂, CuSO₄, and HgCl₂. During this process, aliquots of crude biosurfactant were introduced into different aqueous solutions of metals at 100 mg/mL, and the samples were left to stand for 1 h. The results proved that 1 mL of crude biosurfactant reduced the concentration of metals by 44% (Ag₂SO₄), 48% (FeCl₃), 52% (CoCl₂), 48% (CuSO₄), and 56% (HgCl₂).

Other reports in the literature have proposed alternative approaches for remediating water contaminated with heavy metals. For instance, Tabagari et al. [84] explored the combined action of biosurfactants and microalgae to achieve this goal. They observed that a lipid trehalose biosurfactant could increase the absorption efficiency of copper ions using algae (*Spirulina Plantensis*) by 73%. In comparative tests, the biosurfactant showed a superior activity to Ethylenediaminetetraacetic acid (EDTA), which is a toxic chelating agent.

On the other hand, Jimoh and Lin [68] evaluated the removal of hydrophobic contaminants in water under shaking and static conditions. During the studies, the crude lipopeptide biosurfactant at 500 mg/L was added to contaminated water samples. After incubation, a chemical extraction with dichloromethane was applied to extract the aggregated oil, and its mass was quantified through gravimetric methods. This exact procedure was repeated for synthetic surfactants and fermentation broth. The results showed that agitation conditions (30 °C, 150 rpm, 48 h) favored contaminant removal. Despite the crude biosurfactant performing better for both conditions than the synthetic surfactants,

the fermented broth showed the highest removal percentage performance: 79.2% for motor oil and 77.6% for diesel oil (shaking condition) against 64.1% for motor oil and 60.3% for diesel oil (static condition).

The authors reported that agitation promoted better contact between the biosurfactant and pollutant, thus increasing the removal efficiency. Therefore, all these studies showed that biosurfactants have a strong potential for use in the treatment processes of water contaminated by heavy metals or hydrophobic pollutants.

3.3.3. Bioremediation in Liquid Effluent Samples

Jayalatha and Devatha [76] investigated the degradation capacity of a toxic agent (triclosan) in domestic wastewater using a solution of a lipopeptide biosurfactant produced in crude sunflower oil. An aliquot of this solution was added to contaminated effluent samples at a 1:1 (v/v) volumetric ratio for the bioremediation tests. After different time intervals (2 and 16 h), the samples were analyzed using high-performance liquid chromatography to determine the final concentration of the contaminant. The results showed that the biosurfactant completely removed the triclosan after 16 h, with a removal efficiency of 100%. The study concluded that a longer contact time resulted in a higher pollutant removal rate. In addition, the removal mechanism may have involved the adsorption of the pollutant onto the formed micelles.

Another way to degrade triclosan using wastewater is through biosurfactant-mediated microbial biodegradation. In this context, Guo et al. [85] investigated the aerobic degradation capacity of triclosan using a bacterial community in the presence of a biosurfactant. The study observed that the initial triclosan concentration of 30 µg/g decreased with the addition of sophorolipid biosurfactants at concentrations ranging from 0.125 to 0.5 g/L, resulting in triclosan levels between 16 and 5 µg/g, respectively. The authors reported that biosurfactant concentrations above the critical micellar concentration increased the solubilization and bioavailability of triclosan as a microbial food source, which led to more significant biodegradation.

Jayalatha and Devatha [77] returned to study the degradation of triclosan in domestic effluents using a rhamnolipid biosurfactant synthesized in crude sunflower oil. The research also investigated the degradation of another toxic drug, ibuprofen. In this case, aliquots of the biosurfactant at different concentrations were separately added to the effluent samples in a volumetric ratio of 1:1 (v/v). Then, the samples were analyzed using high-performance liquid chromatography and mass spectrometry to measure the final concentration of contaminants and investigate the presence of possible toxic by-products formed during degradation. The results indicated that the biosurfactant at a CMC of 10 mg/L achieved the highest percentage performances, as it reduced the concentrations of triclosan (0.356 mg/L) and ibuprofen (4.36 mg/L) by 100% and 99.7% after 6 h, respectively. However, 16 h was required to consume the toxic by-products formed during the process.

Focusing on the removal of heavy metals from effluents, França et al. [67] introduced a crude lipopeptide biosurfactant (250 mg/L) into different effluent samples contaminated with heavy metals at 1000 ppm (1 mg/mL). These samples were incubated in an orbital shaker at 30 °C and 150 rpm for different periods. The results showed that the biosurfactant achieved intermediate percentages in removing metals: 86% for copper, 36% for chromium, and 39% for zinc after 48 h. However, the highest percentages occurred in the presence of NaOH for a shorter contact time (24 h). The authors highlighted that an increase in pH may have favored the chelating action of the biosurfactant, which further reduced the concentration of the contaminants. This phenomenon was described by Poirier et al. [86], who evaluated the ability of a biosurfactant to chelate heavy metals in aqueous medium under the influence of pH. The study revealed that increasing the pH of a solution containing a

glycolipid biosurfactant and four heavy metal ions (Cu, Ni, Cr, Co) led to the formation of a metallogel. This gel was formed by the biosurfactant that adsorbed the metal ions into its chemical structure, resulting in removal percentages of 88% (Cu), 80% (Ni), 59% (Cr), and 95% (Co).

In a different approach, Sonde and Di Vakaran [78] produced two biosurfactants from two substrates (palm oil and sunflower oil) and compared their performance in precipitating lead in wastewater. The results showed that the biosurfactant derived from sunflower oil performed better in precipitating the metal. This suggests that the sunflower oil substrate could be a promising alternative for producing biosurfactants with significant potential for precipitating effluent metals.

3.4. Bibliometric Analysis

Bibliometric studies use a series of tools to map the production of academic research, providing a better understanding of the current scenario [87]. Through these tools, it is possible to monitor scientific studies' evolution, trends, and current state [88]. According to Redeker, Kessler, and Kipper [89], bibliometric research can be explored in two ways: performance analysis and scientific mapping. Performance analysis evaluates publications based on the authors, year, source, number of citations, type of documents, countries, and institutions [90,91]. Nonetheless, scientific mapping shows through bibliometric maps how these parameters relate to each other [91]. In this context, VOSviewer software is a powerful tool that offers the option of exploring areas of academic research by combining these two forms of analysis. This study used it to analyze the 12 original articles focused on producing biosurfactants from sunflowers for applications in bioremediation. This analysis was based on the following bibliometric parameters: the most productive journals, publications by country, the most cited articles, keywords, and institutions.

3.4.1. Journals

The articles analyzed were distributed across 12 different journals: the *International Journal of Environmental Science and Technology*, the *Journal of Environmental Management*, the *Egyptian Journal of Chemistry*, the *Bioremediation Journal*, *Molecular Biotechnology*, *Waste and Biomass Valorization*, the *Journal of Environmental Science and Engineering*, *Chemical Engineering Transactions*, *Biotechnology and Bioprocess Engineering*, *Catalysis Today*, the *Research Journal of Pharmaceutical, Biological and Chemical Sciences*, and *Petroleum Science and Technology*. Thus, the software identified that all these journals published only one article, with no emphasis on productivity. The network map shown in Figure 2 illustrates the relationships between these journals.

The lines (links) connecting the nodes (journals) represent the frequency of citations between articles in each journal. Consequently, the stronger the links, the higher the frequency of citations between the articles. Through this map, it is possible to notice a more intense connection between the journals *Molecular Biotechnology* and the *Journal of Environmental Management*, which indicates that the articles published in these journals share the same references. The two works by Jayalatha and Devatha [76,77] that have similar themes were published in these journals, which explains a more solid collaboration between them.

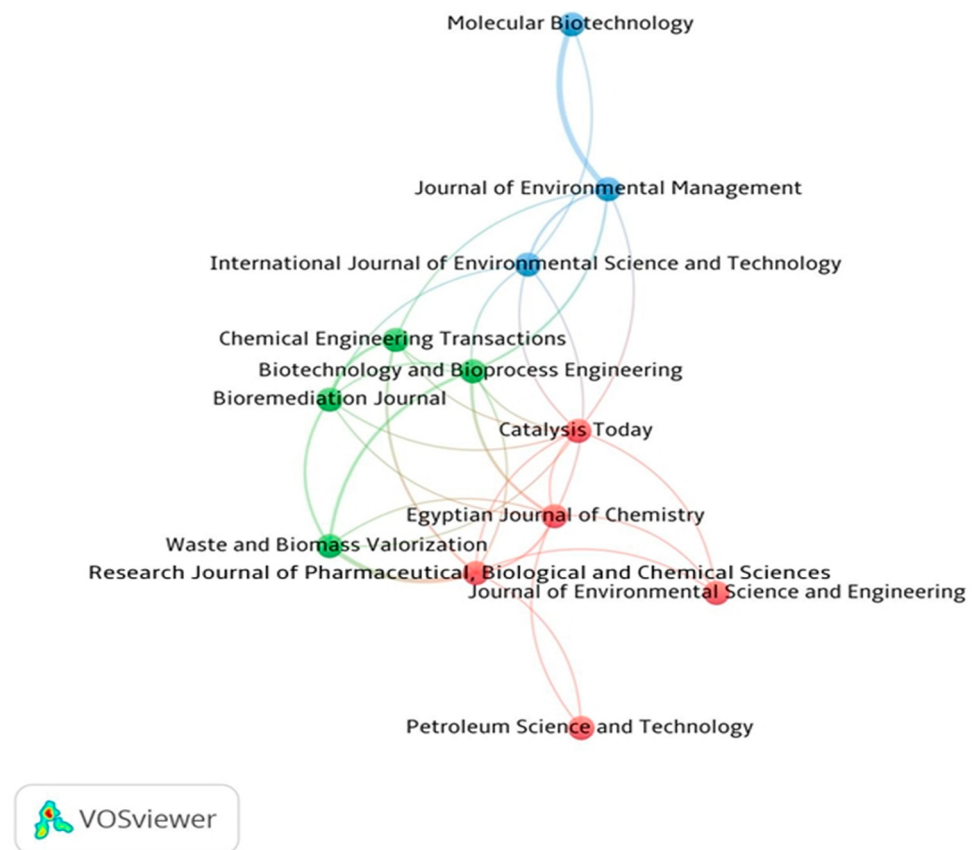


Figure 2. Network mapping of the journals where the articles analyzed were published.

3.4.2. Publications by Country

India had the highest number of publications (3), followed by Brazil (2), China (2), Egypt (2), and South Africa (2). Iran and Turkey came in sequence with only one publication each. Figure 3 confirms this distribution since the larger nodes indicate more published articles. In addition, the links that connect these nodes (countries) demonstrate scientific collaborations between authors of different nationalities.

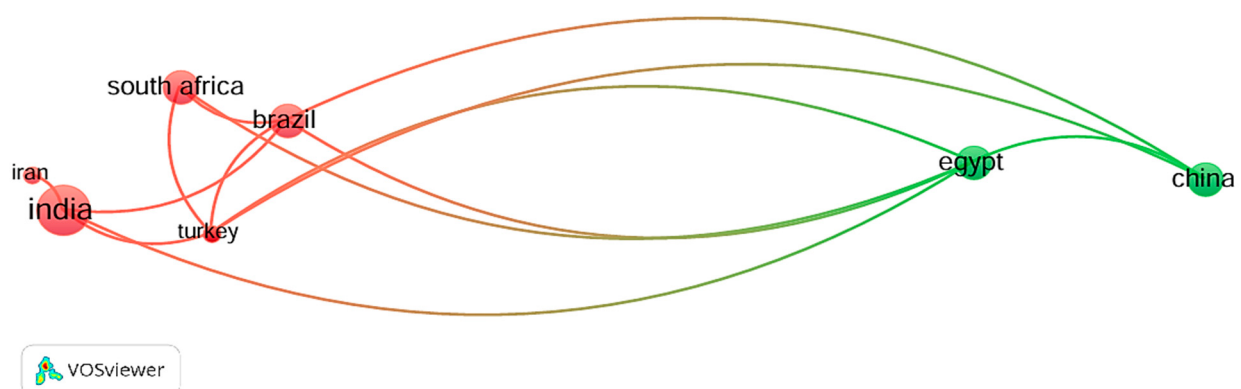


Figure 3. Network mapping of the most productive countries.

Data from FAOSTAT [92] revealed that India consumed the highest amount of sunflower oil as a food source, totaling 1,835,000 tons, followed by South Africa with 330,000 tons, China with 270,000 tons, Egypt with 194,000 tons, and Brazil with 157,000 tons. This high consumption implies a considerable volume of residual oil generated from frying food, which may highlight a growing concern within the country's scientific community regarding its reuse to mitigate environmental issues arising from improper disposal. Ac-

According to Figure 3, the connections between these nodes (countries) illustrate scientific collaborations among authors of diverse nationalities.

3.4.3. Most Cited Articles

Among the various bibliometric indicators used to assess publication quality, citation analysis is one of the most widely applied. When an article is cited by another, it demonstrates the article's value in providing helpful information that contributes to the advancement of further research [93]. In this context, some indicators can be applied to assess publications, such as total citations (TCs), self-citations (SCs), and Field-Weighted Citation Impact (FWCI), which measures how frequently an article is cited relative to other articles in the same field, publication year, and document type. This indicator is calculated by the ratio of the number of citations received by the analyzed article to the average number of citations received by all similar documents in the database over 3 years. FWCI values higher than one indicate that the analyzed article's citation count exceeds the average citation count of similar articles, signifying that it is cited more frequently than expected relative to the global average [94].

To ensure a more reliable analysis, self-citations were also quantified, as authors may sometimes cite their work inappropriately, potentially compromising the accuracy of the data [95]. Table 4 lists the five most cited articles.

Table 4. Most cited articles on biosurfactant production from sunflowers focused on bioremediation applications.

Authors	Journals	TC	SC	FWCI *
França et al. [67]	<i>Catalysis Today</i>	83	7	1.21
Minucelli et al. [73]	<i>Waste and Biomass Valorization</i>	50	8	0.74
Velioglu and Urek [65]	<i>Biotechnology and Bioprocess Engineering</i>	26	0	0.97
Xia et al. [71]	<i>Petroleum Science and Technology</i>	21	4	1.34
Jayalatha and Devatha [76]	<i>Molecular Biotechnology</i>	20	1	0.89

TC: total citations; SC: self-citations; FWCI: Field-Weighted Citation Impact. * Values from 2023.

According to Table 4, it is possible to note that the article entitled “Studies of biosurfactant for microbial enhanced oil recovery by using bacteria isolated from the formation water of a petroleum reservoir”, published by Xia et al. [71], presented the highest FWCI (1.34) and the fourth highest number of citations (21). This study examined the ability of a rhamnolipid biosurfactant, produced using residual sunflower oil, and its producing strain (*Pseudomonas aeruginosa* WJ-1) to remove oil from a compacted sand column. Another highlight was the article “Production of a biosurfactant by *Bacillus subtilis* ICA56 aiming bioremediation of impacted soils”, developed by França et al. [67], which had the second highest FWCI (1.21) and the highest number of citations (83). This paper evaluated the dual action of a lipopeptide biosurfactant produced in residual sunflower oil to remove hydrocarbons in soil and heavy metals in effluents. The FWCI data indicate that these works have been cited more frequently than similar ones (relative relevance). On the other hand, the number of total citations indicated that all the works presented in Table 4, to different degrees, have good overall relevance.

3.4.4. Keywords

Keywords are terms that indicate the central idea present in a study. The authors usually use keywords to guide readers within the topic they are addressing. In addition, reviewers and editors often add more keywords based on the topic to broaden the scope

and facilitate access to these publications, and thus, many keywords may appear during searches [88]. In this sense, the VOSviewer software allows for all keywords in a set of publications to be analyzed.

Before analyzing the keywords in VOSviewer, it was necessary to combine similar ones. For example, “industrial waste” was replaced by “industrial wastes”, and their respective numbers of occurrences were added. Thus, “biosurfactant” was replaced by “bio-surfactants”, and the same was carried out for “bacteria” and “bacterium”. After this procedure, according to the searches, a total of 196 keywords were found. However, three was defined as the minimum number of occurrences to verify which keywords stood out. As a result, 19 keywords were detected. The corresponding network map is presented in Figure 4.

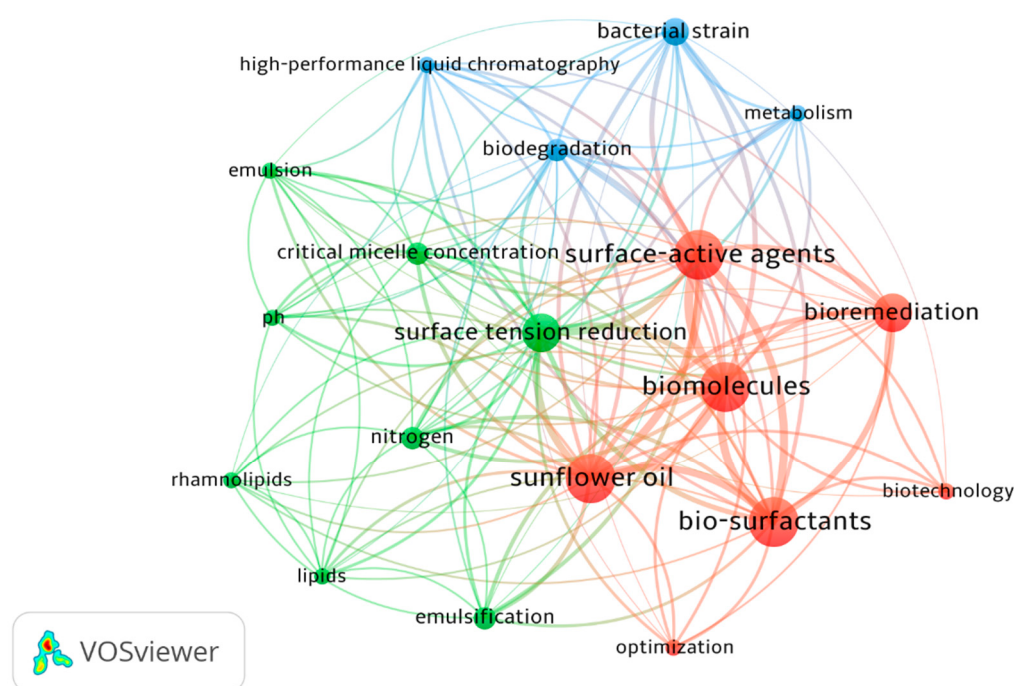


Figure 4. Network mapping of the most frequently occurring keywords.

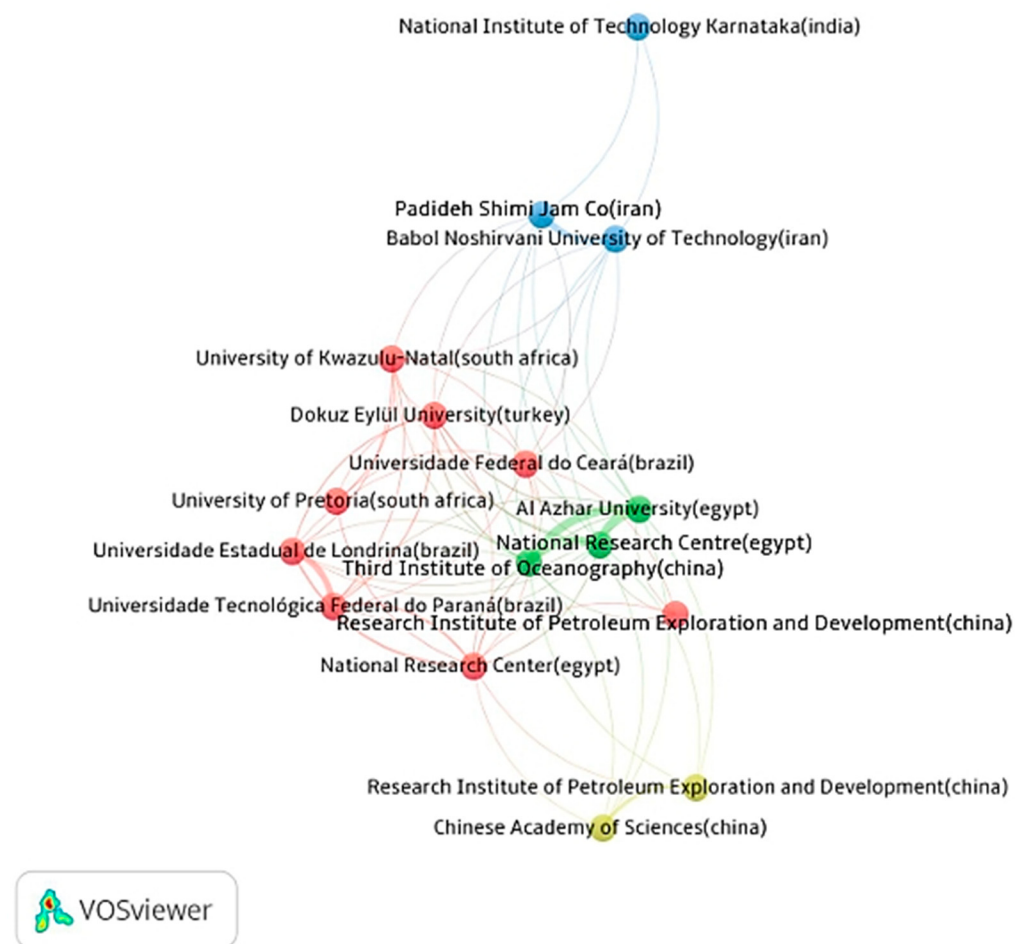
In Figure 4, the keywords are divided into three different clusters, separated by the following colors: green, red, and blue. Analyzing the map, it is possible to notice that the most frequently occurring keywords (larger nodes) were “bio-surfactants”, “biomolecules”, “sunflower oil”, and “surface-active agents” (9), followed by “bioremediation” and “surface tension reduction” (7), as described in Table 5. These terms share a stronger connection, as they are linked by thicker lines and are highlighted in the same color (red). The fact that thicker lines connect these words indicates that they appear simultaneously in the same articles, while the same color indicates that they belong to similar themes. In this context, as biosurfactants, which are known as amphiphilic biomolecules and surface-active agents, were the focus of all the works, this explains why the terms “bio-surfactants”, “biomolecules”, and “surface-active agents” are among the most common. Sunflower oil was the most used substrate for the production of biosurfactants, which explains why the term “sunflower oil” also stood out. Additionally, the prominence of the terms “bioremediation” and “surface-active agents” was linked to the studies conducting bioremediation tests with biosurfactants in various contaminated environments while simultaneously performing surface tension reduction tests to measure the surfactant capabilities of the biosurfactants.

Table 5. Most used keywords.

Keywords	Occurrence
Bio-surfactants	9
Biomolecules	9
Sunflower oil	9
Surface-active agents	9
Bioremediation	7
Surface tension reduction	7
Bacterial strain	5
Critical micelle concentration	4
Emulsification	4
Nitrogen	4

3.4.5. Most Productive Institutions

The retrieved articles originated from 16 distinct institutions, as shown in Figure 5.

**Figure 5.** Network mapping of the most productive institutions.

It is important to note that VOSviewer conducted this analysis considering all contributing institutions, not only those affiliated with the primary author. However, the software found no institutional repetition across different articles, indicating that each institution contributed with only one publication. Therefore, there was no standout institution for productivity.

On the other hand, Brazil, China, and Egypt were the countries with the most significant number of institutions that collaborated on the topic. Each country had two publica-

tions and three different institutions working together to build and publish their research, highlighting solid cooperative efforts in the research development process. Additionally, the links connecting all 16 institutions illustrate existing collaborations, with the strongest links reflecting joint contributions from multiple institutions to the same scientific work. This collaborative approach significantly enhances the development and advancement of research on biosurfactant production from sunflowers for bioremediation applications.

4. Conclusions

Raw materials from sunflowers have a strong potential to reduce costs in the production of biosurfactants and, at the same time, mitigate environmental contamination caused mainly by the inadequate disposal of residual frying oil. Among all the sunflower raw materials, oil was the most used substrate for biosurfactant production. This may be associated with its low cost, recycling, and rich linoleic acid content, which can induce higher biosurfactant yields. In addition, sunflower seed stalks and husks were rarely used for this purpose, reinforcing the need for further studies to explore the sunflower's potential for biosurfactant production.

The selected studies discussed the biosurfactant's excellent capacity to favor biodegradation and the removal of different hydrophobic pollutants in soils, besides reducing the concentration of heavy metals and degrading toxic drugs in aqueous media. Therefore, biosurfactants from sunflowers have great potential for bioremediation processes of contaminated soils, water, and liquid effluents. This reaffirms that using recyclable substrates to produce biosurfactants and their applications in bioremediation can considerably reduce environmental contamination.

Regarding the bibliometric analysis performed by VOSviewer, the network maps made it possible to monitor and visualize the complete scenario regarding the topic addressed and the quality of the publications analyzed. This perspective will assist researchers in selecting relevant keywords for targeted literature searches and simultaneously enable the identification of articles, countries, and institutions as potential collaborators for future developments in the field.

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