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Antimicrobial Potential of Biosurfactants from Microbial Sources: A Bibliometric Analysis

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Abstract

Background. Biosurfactants exhibit exceptional biological activities against pathogenic microorganisms, gaining significant attention for their potential in combating antimicrobial drug resistance. These molecules have been globally studied and widely published in reputable international journals. This study aims to provide a comprehensive bibliometric analysis of the global research profile, utilization, and advancements of biosurfactants as antimicrobial agents over the past three decades.

Methods. Publication data on biosurfactants as antimicrobial agents were obtained from the Scopus database (1991–2023) and analyzed bibliometrically through VOSviewer.

Results. A total of 908 publications, with an annual average of 28 articles, including notable contributions in *Frontiers in Microbiology*, with 43 documents are obtained in this study. Publication trends have shown consistent growth since 2000, peaking in 2022. India emerged as the most prolific contributor, followed by Ulster University as the leading institution and Banat, I.M. as the most productive author. Popular research themes include biosurfactants, antimicrobial activity, and anti-infective agents.

Conclusion. This research offers a brief overview of the utilization of biosurfactants as antimicrobial agents research at a worldwide level from 1991 through 2023. This analysis highlights research trends and provides a foundation for future studies in this field.

Keywords: Antimicrobial agent, Biosurfactant, Bibliometric, VOSviewer

1. Introduction

Antimicrobial resistance stands as one of the greatest challenges rapidly facing modern medicine and public health globally (Rzycki *et al*., 2024). The World Health Organization (WHO) has highlighted that antimicrobials, including antibiotic resistance, pose a major concern to the public health, with the potential to contribute ineffective drugs to treat bacteria to antibiotics due to prolonged and improper antimicrobial use (Rzycki *et al*., 2024; Antimicrobial Resistance Collaborators, 2022; Prastiyanto *et al*., 2024). To solve this urgent problem, researchers and other groups are actively coordinating action plans to develop novel antibiotics and antimicrobial agents. A thorough study and screening process are critical to precisely characterize compounds and define possible targets for tackling antimicrobial resistance and other human diseases.

Natural products (NPs), such as medicinal plants (Anand *et al*., 2019; Manan *et al*., 2022), fungi (Jakubczyk and Dussart, 2020), and endophytic plants have the ability to compete with other microorganisms and are abundant source of antimicrobial compounds. These compounds have unique features when compared to synthetic compounds in terms of structural complexity and enormous scaffold diversity (Atanasov e*t al*., 2021). The phenolic compound of *Ruta chalepensis* L. leaf extract has antimicrobial activity against bacteria, such as *Bacillus cereus*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and fungi like *Candida albicans* (Al-Ghamdi *et al*., 2020). Plants and fungi-based pharmaceuticals have been used in the reduction of human disease for over 5000 years (Hu *et al*., 2019). The endophytic thermophilic fungus *Gymnascella thermotolerans*-GTE-21 on *Euphorbia geniculata* have antimicrobial activity against human pathogenic microbial *Staphylococcus epidermidis* and *Candida ciferrii* (El-Zayat *et al*., 2024). This highlights that natural products are a promising source of antimicrobials, particularly biosurfactants derived from bacteria, fungi, or plants (Figure 1) (Ceresa et al. 2021, Kumar et al. 2021, Sarubbo et al. 2022).

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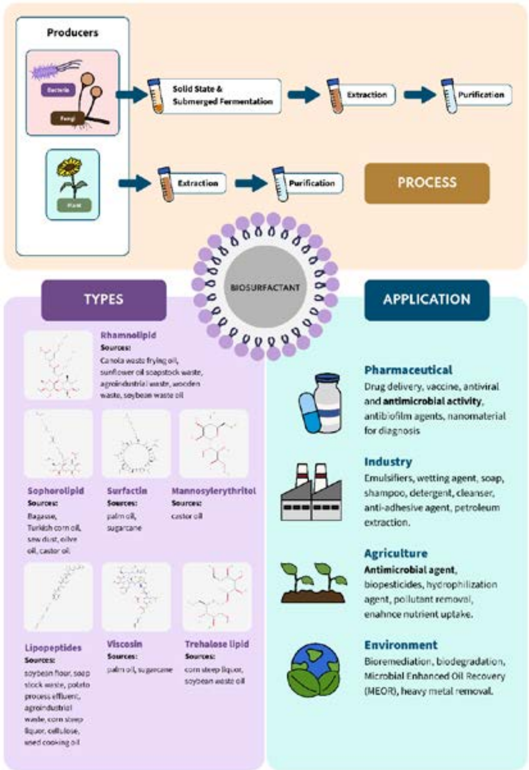


Figure 1. Production, Types, and Application of Biosurfactants.

Biosurfactants belong to surface-active compounds that consist of hydrophobic and hydrophilic moieties of biological origin to encourage the presence of interfaces with different polarities between fluids (Eras-Munoz *et al*., 2022). Biosurfactants possess several benefits compared with chemical surfactants, including being non-toxic, biodegradable, not accumulating in the environment, and stable under several environmental conditions (Alfian *et al*., 2022); thereby providing various future applications, including industrial sectors. These surface-active compounds possess promising biological features against pathogenic microbes in the host organisms, including anti-biofilm (Ali *et al*., 2022; Adnan *et al*., 2023; Kaur and Kaur, 2019), anti-adhesive (Mouafo *et al*., 2023; Firdose *et al*., 2023), and anti-microbial activities (Akgul *et al*., 2019; Adnan *et al*., 2023; Adu *et al*., 2022; AA *et al*., 2020).

Studies in biosurfactants used for treating pathogenic agents in plants and humans are increasing gradually. Low molecular weight groups, like glycolipids and lipopeptides, have been authorized for biological qualities based on their molecular. Glycolipids have been effective therapeutic agents in combating various diseases (Shu *et al*., 2021), including antiadhesive (Kadhum and Haydar, 2020), and antimicrobial properties, such as antifungal (Ayed *et al*., 2023), antibacterial (de Freitas *et al*., 2019; da Fontoura *et al*., 2020), and antiviral effects (Tsuji *et al*., 2023). Nevertheless, lipopeptides showed biocontrol agents against plant pathogens (Huang *et al*., 2022; Ghazala *et al*., 2022; Abdallah *et al*, 2018), antimicrobial impact in food (Ali *et al*., 2022), biofilm inhibition (Englerova *et al*., 2021; Ceresa *et al*., 2021), and antimicrobial (Chauhan *et al*., 2022). Biosurfactants like rhamnolipid produced by *Pseudomonas aeruginosa* ST5 and surfactin from *Bacillus amyloliquefaciens* ST34 have demonstrated efficacy against antibiotic-resistant *Escherichia coli* and *Staphylococcus aureus* (Ndlovu et al., 2017). Similarly, Sambanthamoorthy et al. (2014) reported that biosurfactants from *Lactobacillus jensenii* and *Lactobacillus rhamnosus* exhibit potent antimicrobial and anti-adhesive activities against multidrug-resistant (MDR) strains, including *Acinetobacter baumannii, Escherichia coli*, and methicillin-resistant *Staphylococcus aureus* (MRSA).

The aims of this study was to carry out a bibliometric analysis of the biosurfactants related-research, especially of antimicrobial activities. Bibliometric analysis has been widely used in several research worldwide, such as snake venom, Indonesian biodiversity through DNA barcoding, prevalence of chikungunya cases, prevalence of monkeypox cases, organoid in regenerative medicine also global trends in non-alcoholic fatty acid liver (Sofyantoro *et al*., 2022a; Priyono *et al*., 2023; Sofyantoro *et al*., 2023; Sofyantoro *et al*., 2022b; Setiawan *et al*., 2024; Putri *et al*., 2023). Regarding current bibliometric studies, there is only one that evaluates the output of renewable source production of biosurfactants quantitively and qualitatively (Nunes *et al*., 2022), and no bibliometric studies of biosurfactants as antimicrobial agents. Therefore, evaluation the worldwide research profile of literature on antimicrobial agents of biosurfactants is critical. In order to provide a comprehensive profile of biosurfactants as antimicrobial agents literature for the last three decades, this study mapped collaboration worldwide, evaluated the eminent institutions performance and authors, investigated the output of reputable journals, analyzed the highly cited articles, as well as highlighted arising research topics. The current study findings may present a visual summary of research advancements in this field and assess future research implications.

2. Materials and Methods

This study used data from the Scopus database, selected for its broad journal coverage, which supports both keyword searches and citation analysis. Scopus also indexes journals from other databases (Falagas *et al*., 2008). On February 20, 2024, a bibliometric filter was generated and run using the key terms (TITLE-ABS-KEY (biosurfactant) AND TITLE-ABS-KEY (antimicrobial) OR TITLE-ABS-KEY (antibiotic)) AND (EXCLUDE (PUBYEAR , 2024)) in the title and abstract parts to identify biosurfactants as antimicrobial-related publications from the Scopus database. Type of documents, including key terms, journal titles, publication year, countries, institutions, and citations, were extracted. The data were analyzed with VOSviewer to evaluate global profiles, international and author collaborations and to map prevalent keywords over the past three decades (McAllister *et al*., 2022).

3. Results

3.1. Publication profile of biosurfactant as antimicrobial-related research from 1991 to 2023

Between 1991 and 2023, 908 documents were published worldwide, generating in an average of 28 papers a year related to biosurfactants as anti-microbial agents. Since the 2000s, there has been a steady growth in the amount of research on biosurfactants as antimicrobial agents; the highest number of publications was published in 2022 (112 documents). The highest number published were research articles (n = 679), reviews (n = 142), book chapters (n = 55), and conference papers (n = 14), respectively. English was written in many of the documents (n = 893), followed by Chinese (n = 4), and French (n = 3). Since 1991, the number of documents about biosurfactants as antimicrobial agent has been steadily rising, with the maximum productivity recorded in 2022 (n = 113) (Figure 2).

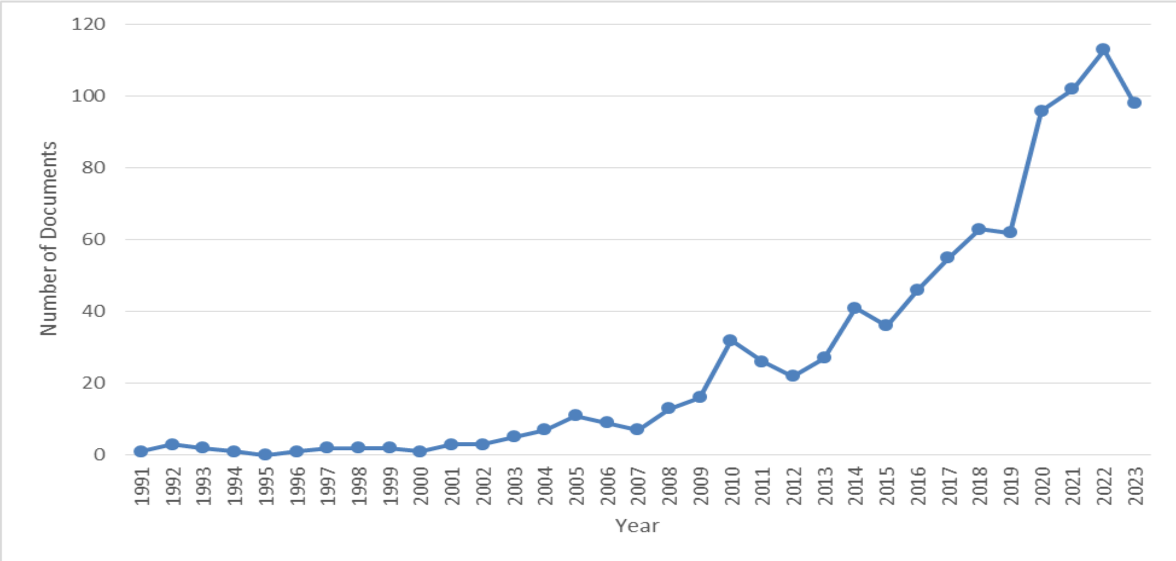


Figure 2. Publication profile of biosurfactant as antimicrobial-related research from 1991 to 2023. 908 documents were obtained from the Scopus database.

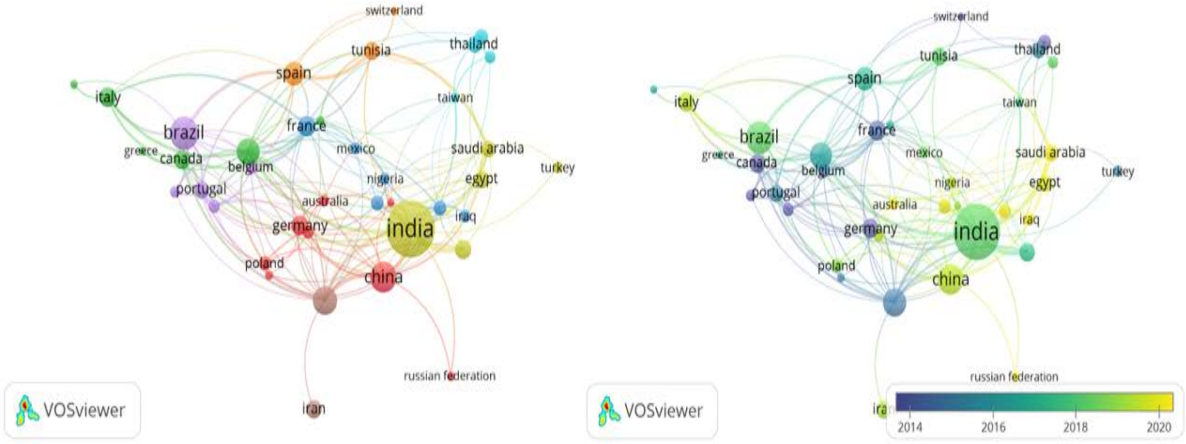
3.2. Collaboration and contribution countries of biosurfactant as antimicrobial-related research during the years 1991-2023

Between 1991-2023, 79 countries contributed to the literature on biosurfactants as antimicrobial agents. The publication shares of the top ten most prolific countries ranged from 26.9% for India to 3.1% for South Korea. Table 1 presents the top ten countries globally related to their relative contribution to the total number of publications. With 245 (26.9%) documents published, India was the top prolific country, followed by Brazil (n = 84, 9.2%), China (n = 72, 7.9%), the United States (n = 64, 7.0%), and the United Kingdom (n = 58, 6.3%) (Table 1). Figure 3a reveals the formation of nine distinct clusters visualized using VOSviewer, each represented by a different color: green (Italy, Canada, Belgium), purple (Brazil, Portugal), red (Germany, Poland, India), dark blue (France, Mexico, Nigeria), yellow (India, Saudi Arabia, Egypt), light blue (Thailand), and orange (Spain, Tunisia). Meanwhile, Figure 3b maps countries based on publication year, with a color gradient from purple to yellow indicating older to more recent publications. The earliest publication year is 2014, while the most recent one is 2020.

Table 1. Collaboration and contribution of the Top Ten Countries for Biosurfactant Research Publications on Antimicrobial Agents Worldwide.

SCR[a]	Country	Number of Documents (%)
1	India	245 (26.9%)
2	Brazil	84 (9.2%)
3	China	72 (7.9%)
4	United States	64 (7.0%)
5	United Kingdom	58 (6.3%)
6	Spain	43 (4.7%)
7	France	34 (3.7%)
8	Germany	31 (3.3%)
9	Italy	30 (3.2%)
10	South Korea	29 (3.1%)

[a]SCR: standard competition ranking.



(a) **(b)**

Figure 3. Mapping the collaboration among countries: The number of collaborations with other countries is reflected in the size of the circle. Visualizations in (a) network and (b) overlay. The size of the circles corresponds to the frequency of appearances. The degree of relationship is indicated by the length of the links. The different colors reveal distinct clusters. The color gradient, from purple to yellow, indicates the timeline from older to more recent publications

3.3. The highest journals of biosurfactant as antimicrobial-related research during the years 1991-2023

Table 2 displays the top fourteen journals with the most documents globally, with 195 (21.47%) documents. Frontiers in Microbiology (n = 43), Colloids and Surfaces B Biointerfaces (n = 15), and Applied Microbiology and Biotechnology (n = 15) were the most published journals on the study of biosurfactants as antimicrobial agents.

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Table 2. The highest journals in the field of biosurfactant research related to antimicrobials.

SCR	Journal	No. of Documents	SJR	H-index
1	“Frontiers in Microbiology”	43 (4.73%)	1.19	233
2	“Applied Microbiology and Biotechnology”	15 (1.65%)	0.968	267
3	“Colloids and Surfaces B Biointerfaces”	15 (1.65%)	0.868	198
4	“Bioresource Technology”	13 (1.43%)	2.473	364
5	“International Journal of Molecular Sciences”	13 (1.43%)	1.154	269
6	“World Journal of Microbiology and Biotechnology”	12 (1.32%)	0.726	115
7	“Applied Biochemistry and Biotechnology”	12 (1.32%)	0.514	135
8	“Pharmaceutics”	11 (1.21%)	0.795	106
9	“Antibiotics”	11 (1.21%)	0.792	77
10	“Scientific Reports”	10 (1.10%)	0.973	315
11	“Process Biochemistry”	10 (1.10%)	0.676	182
12	“Journal of Applied Microbiology”	10 (1.10%)	0.774	185
13	“Current Microbiology”	10 (1.10%)	0.526	108
14	“Biocatalysis And Agricultural Biotechnology”	10 (1.10%)	0.655	70

SCR: standard competition ranking.

3.4. The highest cited article of biosurfactant as antimicrobial-related research during the years 1991-2023

The article titled “Natural functions of lipopeptides from *Bacillus* and *Pseudomonas*: More than surfactants and antibiotics” was the most cited article on biosurfactants as antimicrobial-related research in FEMS Microbiology Reviews (Table 3). The second-highest cited article “Biosurfactant: Potential applications in medicine” published in Journal of Antimicrobial Chemotherapy was co-authored by Banat, I.M who is the first of the top ten authors (Table 5).

Table 3. The most cited articles on biosurfactant as antimicrobial-related research

SCR	Authors	Article title	Journal	Year	Citation
1	Raajimakers *et al*., 2010	"Natural functions of lipopeptides from Bacillus and Pseudomonas: More than surfactants and antibiotics"	FEMS Microbiology Reviews, 34(6), pp. 1037–1062	2010	779
2	Rodrigues *et al*., 2006	"Biosurfactants: Potential applications in medicine"	Journal of Antimicrobial Chemotherapy, 57(4), pp. 609–618	2006	724
3	Abdel-Mawgoud *et al*., 2010	"Rhamnolipids: Diversity of structures, microbial origins and roles"	Applied Microbiology and Biotechnology, 86(5), pp. 1323–1336	2010	656
4	Singh *et al*., 2007	"Surfactants in microbiology and biotechnology: Part 2. Application aspects"	Biotechnology Advances, 25(1), pp. 99–121	2007	595
5	Galie *et al*., 2018	"Biofilms in the food industry: Health aspects and control methods"	Frontiers in Microbiology, 9(MAY), 898	2018	551
6	Singh and Cameotra, 2004	"Potential applications of microbial surfactants in biomedical sciences"	Trends in Biotechnology, 22(3), pp. 142–146	2004	493
7	Reid *et al*., 2011	"Microbiota restoration: Natural and supplemented recovery of human microbial communities"	Nature Reviews Microbiology, 9(1), pp. 27–38	2011	423
8	Thomas *et al*., 2013	"Current developments in solid-state fermentation"	Biochemical Engineering Journal, 81, pp. 146–161	2013	412
9	Elshikh *et al*., 2016	"Resazurin-based 96-well plate microdilution method for the determination of minimum inhibitory concentration of biosurfactants"	Biotechnology Letters, 38(6), pp. 1015–1019	2016	399
10	Van Hamme *et al*., 2006	"Physiological aspects. Part 1 in a series of papers devoted to surfactants in microbiology and biotechnology"	Biotechnology Advances, 24(6), pp. 604–620	2006	390

SCR: standard competition ranking.

3.5. The most productive institutions of biosurfactant as antimicrobial-related research during the years 1991-2023

Table 4 displays the top 10 productive affiliations worldwide in the field of biosurfactants as antimicrobial agents from 1991 to 2023, with a total of 133 (14.64%) documents. Ulster University is the most prolific contributor with 25 (2.73%) biosurfactants as antimicrobial-related documents. Second through fifth on the list were the Universidade de São Paulo (n = 23, 2.51%), Universidade do Minho (18, 1.98%), Universidade de Vigo (n = 16, 1.75%), University of Sfax (n = 13, 1.42%), respectively.

Table 4. The most productive organization in publications related to antimicrobial agents of biosurfactants.

SJR	Affiliation	Country	Number of documents (%)
1	Ulster University	Northern Ireland	25 (2.73%)
2	Universidade de São Paulo	Brazil	23 (2.51%)
3	Universidade do Minho	Portugal	18 (1.98%)
4	Universidade de Vigo	Spain	16 (1.75%)
5	University of Sfax	Tunisia	13 (1.42%)
6	Savitribai Phule Pune University	India	12 (1.31%)
7	Universitat de Barcelona	Spain	11 (1.20%)
8	Universidade Catolica de Pernambuco	Brazil	11 (1.20%)
9	Prince of Songkla University	Thailand	11 (1.20%)
10	Ministry of Education of the People's Republic of China	China	10 (1.09%)

SCR: standard competition ranking.

3.6. The top authors contributed of biosurfactant as antimicrobial-related research during the years 1991-2023

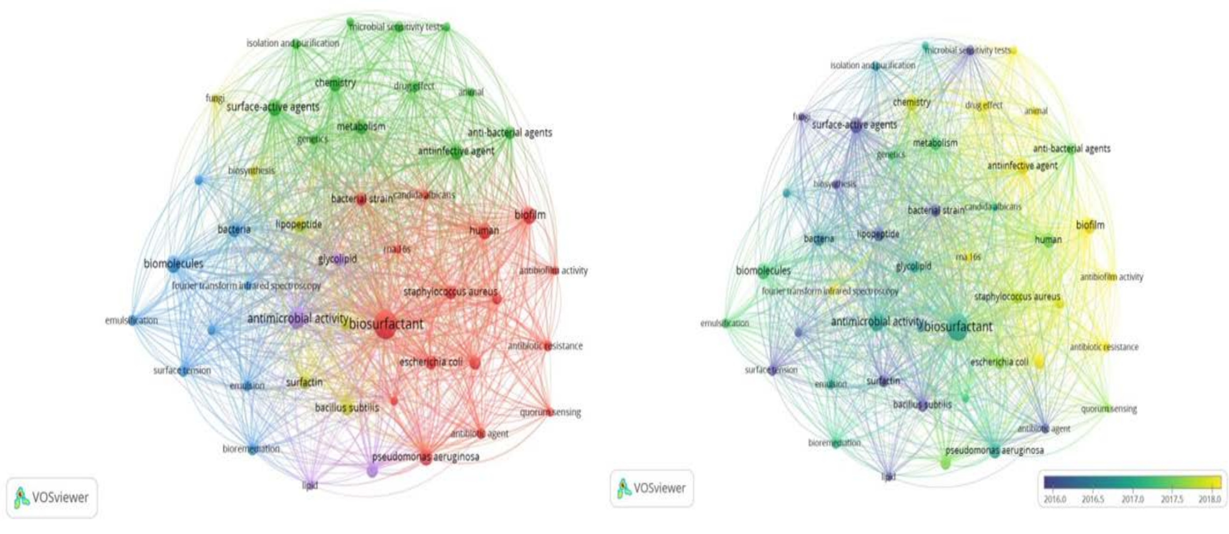
Table 5 displays the top 10 authors worldwide who commit to the field of biosurfactants as antimicrobial agents from 1991 to 2023 according to the amount of document publications. Banat, I.M. is the first of the top ten authors with 24 documents of biosurfactant as microbial-related publication and Vecino, X. is the lowest author with 9 documents.

Table 5. The top ten authors contributed to antimicrobial agents of biosurfactants.

SCR	Authors	No of document	H-index
1	Banat, I.M.	24	80
2	Moldes, A.B.	13	41
3	Cruz, J.M.	12	45
4	Sarubbo, L.A.	12	51
5	Saimmai, A.	11	14
6	Rodríguez-López, L.	11	19
7	Nitschke, M.	11	30
8	Rodrigues, L.R.	10	66
9	Maneerat, S.	10	25
10	Vecino, X.	9	28

SCR: standard competition ranking.

Figure 4 maps the occurrence of terms extracted from 908 documents about biosurfactants as antimicrobial agents indexed by Scopus. Of the 8603 terms that were retrieved, 81 were determined in more than 50 occurrences, leading to the formation of 5 distinct clusters: red, purple, blue, yellow, and green. (Figure 4a). Terms like antibiofilm activity, antibiotic agent, antibiotic resistance, biosurfactant, bacterial strain, *Candida albicans*, biofilm, *Escherichia coli*, human, hydrophobicity, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, 16s RNA, quorum sensing are present in cluster 1 (red color); cluster 2 (green color): animal, anti-bacterial agents, antiinfective agent, chemistry, drug effect, genetics, Isolation and purification, metabolism, microbial sensitivity test, surface-active agents; cluster 3 (blue color): bacteria, biomolecules, bioremediation, emulsification, emulsion, Fourier transform infrared spectroscopy, surface tension; cluster 4 (yellow color): antifungal activity, *Bacillus subtilis*, biosynthesis, fungi, lipopeptide, surfactin; cluster 5 (purple color): antimicrobial activity, glycolipid, lipid, rhamnolipid. In Figure 4b, the extracted terms are categorized by VOSviewer into a color gradient that represents old to recent publishing years, ranging from blue to yellow. Several key terms including antibiotic agent, biosynthesis, bacterial strain, lipopeptide, surfactin, lipid, surface-active agents, surface tension, and *Bacillus subtilis* were deciphered upon in the early years of biosurfactant research as it pertained to antimicrobials. Meanwhile, some keywords like animal, chemistry, drug effect, anti-infective agent, antibiofilm activity, antibiotic resistance, biofilm, Fourier transform infrared spectroscopy, and 16s RNA are the topics that have appeared in recent years.



(a) (b)

Figure 4. Mapping of occurrence terms retrieved from titles and abstracts in biosurfactant as antimicrobial-related research articles conducted by VOSviewer. Visualizations in (a) network and (b) overlay. The circles' sizes correspond to the frequency of appearances. The degree of relationship is indicated by the length of the link. The different colors reveal distinct clusters. The color gradient, from purple to yellow, indicates the timeline from older to more recent publications

4. Discussion

Biosurfactants can be classified as either low-molecular-weight or high–molecular–weight biosurfactants (Kubicki *et al*., 2019). Lipopolysaccharides, lipoproteins, and a combination of these types belong to high-molecular-weight biosurfactants (Kubicki *et al*., 2019), while low-molecular-weight biosurfactants include fatty acids, phospholipids, glycolipids, polyketideglycosides, lipopeptides, and spiculisporic acid (Vieira *et al*., 2021). Moldes et al. (2021) reported glycolipopeptides and glycopeptides as the least studied microbial biosurfactants. Both glycopeptides and glycolipopeptides have been investigated and reviewed for their antimicrobial ability (Butler *et al*., 2014; Vecino *et* *al*., 2018; Acharya *et al*., 2022). Glycolipids and lipopeptides are the most investigated biosurfactant classes for antimicrobial properties as shown in Supplementary 1 and Supplementary 2.

Polymyxins biosurfactants from bacteria were first reported in 1947 as one of the earliest classes of antibiotic, and in 1949, polymyxin E from *Paenibacillus polymyxa* was produced (Ledger *et al*., 2022). However, several adverse effects, including neuromuscular blockade, nephrotoxicity, and neurotoxicity as well as the availability of less toxic antimicrobials, caused it to lose popularity (Grill and Maganti, 2011). Glycopeptides as antibiotics from actinomycetes were discovered and reported in 1954 and introduced clinically in 1958 (Hutchings *et al*., 2019). Iturin as an interesting lipopeptide for antimicrobial and antifungal activity (Yaraguppi *et al*., 2023). Furthermore, a review article titled "Natural functions of lipopeptides from *Bacillus* and *Pseudomonas*: More than surfactants and antibiotics" published in FEMS Microbiology Reviews (Raajimakers *et al*., 2010) was the most cited article on biosurfactants as antimicrobial-related research, indicating that lipopeptide has gained attention in this study.

Based on our findings, India is the most prolific country in terms of antimicrobial properties of biosurfactants research. Biosurfactant research is gradually increasing together with a remarkable market surge in growth for biosurfactant demand in India (TechSci Research, 2023). This trend is especially apparent in personal care products that use antimicrobial natural ingredients. Starting in 2016, the number of published documents significantly increased, and the highest number was in 2022, indicating the field of antimicrobial properties of biosurfactants had high research productivity in recent years. In the research progress of antimicrobial properties of biosurfactant, Saudi Arabia, Egypt, and Iraq contributed as collaboration countries besides developed countries. This result differs from the institution's productivity in publications related to antimicrobial agents of biosurfactants. Ulster University from Northern Ireland has the most number of documents on antimicrobial properties of biosurfactant-related research.

Frontiers in Microbiology was listed as the most prominent journal with many documents discussing the antimicrobial properties of biosurfactants in this study. The first publication from *Frontiers in Microbiology* obtained in this study was published in 2014 titled "Analysis of biosurfactants from industrially viable *Pseudomonas* strain isolated from crude oil suggests how rhamnolipids congeners affect emulsification property and antimicrobial activity" by Das and colleagues from China (Das *et al*., 2014). *Frontiers in Microbiology* journal contributed 4.73% (n = 43) of the total publications retrieved from the Scopus database. Interestingly, although the oldest article related to antimicrobial properties of biosurfactants in *Colloids and Surfaces B Biointerfaces* journal was published in 1996 (Araki *et al*., 1996), this journal was identified as having the third-highest number of published documents 1.65% (n = 15).

The highest citations of research articles in Table 3 emphasize the most significant studies in biosurfactants as research with an antimicrobial focus. They can be used as references in finding present trends and prospects. According to the cluster formed (Figure 4), the red color (cluster 1) indicated the biological activity of biosurfactant and pathogen-caused infection. The green color (cluster 2) indicated the relationship between biosurfactant properties within organisms and their drug combination. The blue color (cluster 3) showed the characterization of biosurfactants, followed by the yellow color showed certain biosurfactants (lipopeptide and surfactin) with their antifungal activity. The purple color showed the major biosurfactants studied, such as glycolipid and rhamnolipid with their antimicrobial activity. As shown in Figure 4, biosurfactant research starting in 2017 has the emerging trend research in several keywords, such as animal, chemistry, drug effect, anti-infective agent, antibiofilm activity, antibiotic resistance, biofilm, Fourier transform infrared spectroscopy, and rna 16s.

Antimicrobial resistance like antibiotic resistance in 2019 caused 1.27 million deaths globally (Antimicrobial Resistance Collaborators, 2022). Exploration of natural compounds particularly biosurfactants for tackling human disease due to antimicrobial resistance is interesting among researchers worldwide. Several studies have demonstrated the biological activity of biosurfactants in vivo or cell line animals like mice (Huang *et al*., 2018; Tsuji *et al*., 2023), human cells (Vazquez *et al*., 2018), mouse fibroblast and mouse macrophage cell lines (Farias *et al*., 2019), chorioallantoic membrane (Rodriguez-Lopez *et al*., 2019), and *Aedes aegypti* larvae (de Andrade Teixeira Fernandes *et al*., 2020). Biosurfactants are capable of degrading microbial cell membranes. These molecules, composed of a hydrophilic head and a hydrophobic tail, interact with bacterial membrane lipids, leading to cellular damage. The mechanism begins with biosurfactants binding to lipopolysaccharides and peptidoglycan in the bacterial membrane, followed by their accumulation on the membrane surface. Furthermore, biosurfactants disrupt membrane proteins, triggering membrane disintegration and ultimately causing bacterial cell lysis (Lourenco *et al*., 2024; Adu *et al*., 2020).

Biofilm formation enhances antimicrobial resistance by increasing bacterial metabolism and strengthening defenses against antimicrobial agents (Uruen *et al*., 2020; Zhao *et al*., 2023). Many studies informed the antibiofilm potential of biosurfactants on the host or medical devices (Supplementary 3). Biosurfactants form micelles that interact with bacterial membranes, modifying the hydrophobic layer to inhibit biofilm formation and adhesion. They also alter surface tension and membrane permeability, causing membrane leakage (Jimoh *et al.*, 2023). Moreover, the established combination formula of biosurfactant to combat antibiotic resistance and multidrug-resistant (MDR) strains has also been reported including nanoparticle-promising technology (Supplementary 4) (Falakaflaki *et al*., 2022; Diaz De Rienzo *et al*., 2016; Arif *et al*., 2021; Amirinejad *et al.*, 2023; Sharaf *et al.*, 2022; Giordani *et al.*, 2019; Lin *et al.*, 2023). Combining natural and synthesized compounds, this technology possesses a synergetic action against antimicrobial resistance compared to biosurfactants or drugs alone. Additionally, this strategy developed widespread biosurfactant applications related to the keyword "drug effect" on the host.

Several methods exist to investigate biosurfactant composition (Barale *et al*., 2022; Gharaei *et al*., 2022; Sen *et al*., 2017), such as Thin Layer Chromatography (TLC), nuclear magnetic resonance (NMR), high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), liquid chromatography-mass spectrometry (LC-MS), and Fourier transform infrared spectroscopy (FTIR). In this study, FTIR is the prominent compositional analysis to determine the functional groups of biosurfactant compounds (Arif *et al*., 2021; Nataraj *et al*., 2021; AA *et al*., 2020; Alfian *et al*., 2022; Athira *et al*., 2021; Challaraj Emmanuel *et al*., 2019;). On the other hand, the established technique for identifying biosurfactant-producing bacterial strains was 16S rRNA gene sequence analysis (Saleh *et al*., 2019; Rani *et al*., 2020; Englerova *et al*., 2021; Elkhawaga *et al*., 2018; Cheffi *et al*., 2021; Reddy *et al*., 2018; Buonocore *et al*., 2020; Challaraj Emmanuel *et al*., 2019) besides biosurfactant-producing yeast strains using rDNA regions (the D1/D2 LSU domains and ITS) (Sen *et al*., 2017). Interestingly, Villela *et al*., (2023) carried out whole-genome gene markers not just the 16S rRNA gene to identify strains. The result showed identified strains differed from the original paper.

5. Future Perspective

Biosurfactants have recently drawn the attention of the research area on drug-delivery systems, pharmaceuticals, and especially antimicrobial resistance. Firstly, further exploration of the functional roles of biosurfactants could enhance our understanding of their impacts on tackling human diseases. Moreover, the exploration of biosurfactants is boundless from direct producers like bacteria, plants, and fungi, yet it can be produced by producers associated with animals and sponges. On the other hand, the adverse effect due to the interaction of the properties should be emphasized especially for differences in application effects. The challenges regarding the cost and effectiveness of biosurfactant applications are important to be resolved.

6. Conclusion

A total of 908 documents have been published over three decades, with an average of 28 publications per year. Most publications were reported in 2022. India emerged as the leading country in publication volume, while Ulster University ranked as the top institution. Banat, I.M. was identified as the most prolific author. Prominent keywords in this research include biosurfactants, antimicrobial activity, and anti-infective agents. In summary, the data provided in this study illustrates the advancements made in the scope of biosurfactants research focusing on their antimicrobial properties from 1991 to 2023, and it may help provide insights for future research.

7. Limitations of Study

A limitation of this study is that it primarily focuses on data from Scopus databases, which may not include all consistent publications. Additionally, the selection of keywords and filters could unintentionally narrow the scope, possibly skewing results toward particular research areas or geographic regions. Another limitation is the potential impact of publication bias, where studies with more favorable or significant results are more likely to be published, potentially leading to an overestimation of the antimicrobial potential of biosurfactants. Lastly, the timing of publications could influence trends observed in the analysis, with surges in publication frequency possibly reflecting external factors such as increased funding or interest rather than true advancements in the field.

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References

A A, E.K R and Mathew J. 2020. Characterization of biosurfactant produced by the endophyte *Burkholderia* sp. WYAT7 and evaluation of its antibacterial and antibiofilm potentials. *J Biotechnol*., **313**: 1-10.

Abdallah DB, Tounsi S, Gharsallah H, Hammami A and Frikha-Gargouri O. 2018. Lipopeptides from *Bacillus amyloliquefaciens* strain 32a as promising biocontrol compounds against the plant pathogen *Agrobacterium tumefaciens*. *Environ Sci Pollut Res*., **25(36)**: 36518-29.

Abdel-Mawgoud AM, Lépine F and Déziel E. 2010. Rhamnolipids: Diversity of structures, microbial origins and roles. *Appl Microbiol Biotechnol*., **86(5)**: 1323-36.

Acharya Y, Bhattacharyya S, Dhanda G and Haldar J. 2022. Emerging roles of glycopeptide antibiotics: Moving beyond gram-positive bacteria. *ACS Infect Dis*., **8(1)**: 1-28.

Adnan M, Siddiqui AJ, Noumi E, Ashraf SA, Awadelkareem AM, Hadi S, Snoussi M, Badraoui R, Bardacki F, Sachidanandan M and Patel M. 2023. Biosurfactant derived from probiotic *Lactobacillus acidophilus* exhibits broad-spectrum antibiofilm activity and inhibits the quorum sensing-regulated virulence. *Biomol Biomed*., **23(6)**: 1051-68.

Adu SA, Naughton PJ, Marchant R and Banat IM. 2020. Microbial biosurfactants in cosmetic and personal skincare pharmaceutical formulations. *Pharmaceutics*., **12(11)**:1099.

Akgul O, Erginkaya Z, Konuray G and Turhan EU. 2019. Antibacterial and anti-adhesive properties of biosurfactants produced by yeasts from food waste. *Fresenius Environ Bull*., **28(5)**: 4283-92.

Alfian AR, Watchaputi K, Sooklim C and Soontorngun N. 2022. Production of new antimicrobial palm oil-derived sophorolipids by the yeast *Starmerella riodocensis* sp. nov. against *Candida albicans* hyphal and biofilm formation. *Microb Cell Fact*., **21(1)**: 163.

Al-Ghamdi AY, Fadlelmula AA and Abdalla MOM. 2020. Total phenolic content, antioxidant and antimicrobial activity of *Ruta chalepensis* L. leaf extract in Al-Baha Area, Saudi Arabia. *Jordan J Biol Sci*., **13(6)**: 675-680.

Ali N, Pang Z, Wang F, Xu B and El-Seedi HR. 2022. Lipopeptide Biosurfactants from *Bacillus* spp.: Types, production, biological activities, and applications in food. *J Food Qual*., **2022(1)**: 1-19.

Ali SAM, Sayyed RZ, Mir MI, Khan MY, Hameeda B, Alkhanani MF, Haque S, Al Tawaha ARM and Poczai P. 2022. Induction of systemic resistance in maize and antibiofilm activity of surfactin from *Bacillus velezensis* MS20. *Front Microbiol*, **13**: 879739.

Amer MA, Wasfi R and Hamed SM. 2023. Biosurfactant from *Nile Papyrus* endophyte with potential antibiofilm activity against global clones of *Acinetobacter baumannii*. *Front Cell Infect Microbiol*., **13**: 1210195.

Amirinejad N, Shahriary P and Hassanshahian M. 2023. Investigation of the synergistic effect of glycolipid biosurfactant produced by *Shewanella algae* with some antibiotics against planktonic and biofilm forms of MRSA and antibiotic resistant *Acinetobacter baumannii*. *World J Microbiol Biotechnol*., **39(2)**: 45.

Anand U, Jacobo-Herrera N, Altemimi A and Lakhssassi N. 2019. A comprehensive review on medicinal plants as antimicrobial therapeutics: potential avenues of biocompatible drug discovery. *Metabolites*., **9(11)**: 258.

Ankulkar R and Chavan M. 2019. Characterisation and application studies of sophorolipid biosurfactant by *Candida tropicalis* RA1. *J Pure Appl Microbiol*., **13(3)**: 1653-65.

Antimicrobial Resistance Collaborators. 2022. Global burden of bacterial antimicrobial resistance in 2019: A systematic analysis. *Lancet*., **399(10325)**: 629-55.

Antolak H, Mizerska U, Berłowska J, Otlewska A and Kręgiel D. 2018. Quillaja saponaria saponins with potential to enhance the effectiveness of disinfection processes in the beverage industry. *Applied Sciences*., **8(3)**: 368.

Araki YI, Lee S, Sugihara G, Furuichi M, Yamashita S and Ohseto F. 1996. New cationic surfactants derived from bile acids: Synthesis and thermodynamic and biophysicochemical properties such as membrane perturbation and protein solubilizing abilities. *Colloids Surf B Biointerfaces*., **8(1-2)**: 81-92.

Argentin MN, Martins LF, Sousa MP and Bossolan NRS. 2023. Biosurfactant from a thermo-halophilic strain of *Bacillus alveayuensis* isolated from a Brazilian oil reservoir: Production, chemical characterization, antimicrobial activity, and efficiency in wettability reversal and oil removal from oil-soaked sand. *Geoenergy Sci Eng*., **231**: 212324.

Arif M, Sharaf M, Khan S, Chi Z and Liu CG. 2021. Chitosan-based nanoparticles as delivery-carrier for promising antimicrobial glycolipid biosurfactant to improve the eradication rate of *Helicobacter pylori* biofilm. *J Biomater Sci Polym Ed*., **32(6)**: 813-32.

Atanasov AG, Zotchev SB, Dirsch VM, International Natural Product Sciences T and Supuran CT. 2021. Natural products in drug discovery: advances and opportunities. *Nat Rev Drug Discov*., **20(3)**: 200-16.

Athira K, Gurrala L and Kumar DVR. 2021. Biosurfactant-mediated biosynthesis of CuO nanoparticles and their antimicrobial activity. *Appl Nanosci (Switzerland)*., **11(4)**: 1447-57.

Ayed A, Essid R, Mankai H, Echmar A, Fares N, Hammami M, Sewald N, Limam F, Tabbene O. 2023. Synergistic antifungal activity and potential mechanism of action of a glycolipid-like compound produced by *Streptomyces blastmyceticus* S108 against *Candida* clinical isolates. *J Appl Microbiol*., **134(11)**: lxad246.

Barale SS, Ghane SG and Sonawane KD. 2022. Purification and characterization of antibacterial surfactin isoforms produced by *Bacillus velezensis* SK. *AMB Express*., **12(1)**: 7.

Bezerra KGO, Silva IGS, Almeida FCG, Rufino RD and Sarubbo LA. 2021. Plant-derived biosurfactants: Extraction, characteristics and properties for application in cosmetics. *Biocatal Agric Biotechnol*., **34**: 102036.

Buonocore C, Tedesco P, Vitale GA, Esposito FP, Giugliano R, Monti MC, D'Auria MV and de Pascale D. 2020. Characterization of a new mixture of mono-rhamnolipids produced by *Pseudomonas gessardii* isolated from edmonson point (antarctica). *Mar Drugs*., **18(5)**: 269.

Butler MS, Hansford KA, Blaskovich MA, Halai R and Cooper MA. 2014. Glycopeptide antibiotics: Back to the future. *J Antibiot (Tokyo)*., **67(9)**: 631-44.

Ceresa C, Rinaldi M, Tessarolo F, Maniglio D, Fedeli E, Tambone E, Caciagli P, Banat IM, De Rienzo MAD and Fracchia L. 2021. Inhibitory effects of lipopeptides and glycolipids on C. *albicans*–*Staphylococcus* spp. dual-species biofilms. *Front Microbiol*., **11**: 545654.

Ceresa, Chiara, Letizia Fracchia, Emanuele Fedeli, Chiara Porta, and Ibrahim M. Banat. 2021. Recent advances in biomedical, therapeutic and pharmaceutical applications of microbial surfactants. Pharmaceutics., 13(4): 466.

Challaraj Emmanuel ES, Sree Priya S and George S. 2019. Isolation of biosurfactant from *Lactobacillus* sp. and study of its inhibitory properties against E.*coli* Biofilm. *J Pure Appl Microbiol*., **13(1)**: 403-11.

Chauhan V, Dhiman VK and Kanwar SS. 2022. Purification and characterization of a novel bacterial Lipopeptide(s) biosurfactant and determining its antimicrobial and cytotoxic properties. *Process Biochem*., **120**:114-25.

Cheffi M, Maalej A, Mahmoudi A, Hentati D, Marques AM, Sayadi S and Chamkha M. 2021. Lipopeptides production by a newly *Halomonas venusta* strain: Characterization and biotechnological properties. *Bioorg Chem*., **109**: 104724.

Clements T, Ndlovu T and Khan W. 2019. Broad-spectrum antimicrobial activity of secondary metabolites produced by *Serratia marcescens* strains. *Microbiol Res*., **229**: 126329.

da Fontoura ICC, Saikawa GIA, Silveira VAI, Pan NC, Amador IR, Baldo C, de Rocha SPD and Celligoi MAPC. 2020. Antibacterial activity of sophorolipids from *Candida bombicola* against human pathogens. *Braz Arch Biol Technol*., **63**: e20180568.

Da Silva GO, Farias BCS, Da Silva RB, Teixeira EH, Cordeiro RDA, Hissa DC and Melo VMM. 2021. Effects of lipopeptide biosurfactants on clinical strains of *Malassezia furfur* growth and biofilm formation. *Med Mycol*., **59(12)**: 1191-201.

Das P, Yang XP and Ma LZ. 2014. Analysis of biosurfactants from industrially viable *Pseudomonas* strain isolated from crude oil suggests how rhamnolipids congeners affect emulsification property and antimicrobial activity. *Front Microbiol*., **5**: 696.

de Andrade Teixeira Fernandes N, de Souza AC, Simões LA, Ferreira dos Reis GM, Souza KT, Schwan RF and Dias DR. 2020. Eco-friendly biosurfactant from *Wickerhamomyces anomalus* CCMA 0358 as larvicidal and antimicrobial. *Microbiol Res*., **241**: 126571.

de Freitas Ferreira J, Vieira EA and Nitschke M. 2019. The antibacterial activity of rhamnolipid biosurfactant is pH dependent. *Food Res Int*., **116**: 737-44.

de Souza Freitas F, Coelho de Assis Lage T, Ayupe BAL, de Paula Siqueira T, de Barros M and Tótola MR. 2020. *Bacillus subtilis* TR47II as a source of bioactive lipopeptides against gram-negative pathogens causing nosocomial infections. *Biotech*., **10(11)**: 474.

Diaz De Rienzo MA, Stevenson PS, Marchant R and Banat IM. 2016. Effect of biosurfactants on *Pseudomonas aeruginosa* and *Staphylococcus aureus* biofilms in a BioFlux channel. *Appl Microbiol Biotechnol*., **100(13)**: 5773-9.

Dong S, Yang X, Zhao L, Zhang F, Hou Z and Xue P. 2020. Antibacterial activity and mechanism of action saponins from *Chenopodium quinoa* Willd. husks against foodborne pathogenic bacteria. *Ind Crops Prod*., **149**: 112350.

Elkhawaga MA. 2018. Optimization and characterization of biosurfactant from *Streptomyces griseoplanus* NRRL-ISP5009 (MS1). *J Appl Microbiol*., **124(3)**: 691-707.

Elshikh M, Ahmed S, Funston S, Dunlop P, McGaw M, Marchant R and Banat IM. 2016. Resazurin-based 96-well plate microdilution method for the determination of minimum inhibitory concentration of biosurfactants. *Biotechnol Lett*., **38(6)**: 1015-9.

El-Zayat SA, Kamel NM, Abdel-Motaal FF, El-Sayed MA, Abdelrahman M, Abou-Ellail M, Mohamed AEH and Darwish DB. 2024. *Gymnascella thermotolerans*-GTE-21, an endophytic Fungus in *Euphorbia geniculata* as a Versatile Producer of Bioactive Metabolites. *Jordan J Biol Sci*., **17(1)**: 363-374.

Englerová K, Bedlovičová Z, Nemcová R, Király J, Mad'ar M, Hajdučková V, Stykova E, Mucha R and Reiffova K. 2021. *Bacillus amyloliquefaciens* - derived lipopeptide biosurfactants inhibit biofilm formation and expression of biofilm-related genes of *Staphylococcus aureus*. *Antibiotics*., **10(10)**: 1252.

Eras-Munoz E, Farre A, Sanchez A, Font X and Gea T. 2022. Microbial biosurfactants: a review of recent environmental applications. *Bioengineered*., **13(5)**: 12365-91.

Falagas ME, Pitsouni EI, Malietzis GA and Pappas G. 2008. Comparison of PubMed, Scopus, Web of Science, and Google Scholar: Strengths and weaknesses. *FASEB J*., **22(2)**: 338-342.

Falakaflaki M, Varshosaz J and Mirian M. 2022. Local delivery of usnic acid loaded rhamnolipid vesicles by gelatin /tragacanth gum/montmorillonite/vanillin cryogel scaffold for expression of osteogenic biomarkers and antimicrobial activity. *J Drug Deliv Sci Technol*., **69**: 103147.

Farias JM, Stamford TCM, Resende AHM, Aguiar JS, Rufino RD, Luna JM and Sarubbo LA. 2019. Mouthwash containing a biosurfactant and chitosan: An eco-sustainable option for the control of cariogenic microorganisms. *Int J Biol Macromol*., **129**: 853-60.

Firdose A, Chong NHH, Ramli R and Aqma WS. 2023. Antimicrobial, antiadhesive, and antibiofilm actions of rhamnolipids on ESKAPE pathogens. *Lett Appl Microbiol*., **76(2)**: ovad013.

Galié S, García-Gutiérrez C, Miguélez EM, Villar CJ and Lombó F. 2018. Biofilms in the food industry: Health aspects and control methods. *Front Microbiol*., **9**: 898.

Gharaei S, Ohadi M, Hassanshahian M, Porsheikhali S and Forootanfar H. 2022. Isolation, optimization, and structural characterization of glycolipid biosurfactant produced by marine isolate *Shewanella algae* B12 and evaluation of its antimicrobial and anti-biofilm activity. *Appl Biochem Biotechnol*., **194(4)**: 1755-74.

Ghazala I, Charfeddine S, Charfeddine M, Gargouri-Bouzid R, Ellouz-Chaabouni S and Haddar A. 2022. Antimicrobial and antioxidant activities of *Bacillus mojavensis* I4 lipopeptides and their potential application against the potato dry rot causative *Fusarium solani*. *Arch Microbiol*., **204(8)**: 484.

Giordani B, Costantini PE, Fedi S, Cappelletti M, Abruzzo A, Parolin C, Foschi C, Frisco G, Calonghi N, Cerchiara T, Bugucci F, Luppi B and Vitali B. 2019. Liposomes containing biosurfactants isolated from *Lactobacillus gasseri* exert antibiofilm activity against methicillin resistant *Staphylococcus aureus* strains. *Eur J Pharm Biopharm*., **139**: 246-52.

Grill MF and Maganti RK. 2011. Neurotoxic effects associated with antibiotic use: management considerations. *Br J Clin Oharmacol*., **72(3)**: 381–393.

Haba E, Pinazo A, Jauregui O, Espuny MJ, Infante MR and Manresa A. 2003. Physicochemical characterization and antimicrobial properties of rhamnolipids produced by *Pseudomonas aeruginosa* 47T2 NCBIM 40044. *Biotechnol Bioeng*., **81(3)**: 316-22.

Haddaji N, Bahloul B, Bahia W, Bechambi O and Mahdhi A. 2023. Development of nanotechnology-based drug delivery systems for controlling clinical multidrug-resistant *Staphylococcus aureus* and *Escherichia coli* Associated with aerobic vaginitis. *Pharmaceutics*., **15(8)**: 2133.

Henkel M and Hausmann R. 2019. Chapter 2 - Diversity and Classification of Microbial Surfactants. In: Hayes DG, Solaiman DKY and Ashby RD (Eds). **Biobased Surfactants (Second Edition).** AOCS Press, pp. 41-63.

Hu H, Shen X, Liao B, Luo L, Xu J and Chen S. 2019. Herbgenomics: A stepping stone for research into herbal medicine. *Sci China Life Sci*., **62(7)**: 913-20.

Huang W, Lang Y, Hakeem A, Lei Y, Gan L and Yang X. 2018. Surfactin-based nanoparticles loaded with doxorubicin to overcome multidrug resistance in cancers. *Int J Nanomed*., **13**: 1723-36.

Huang Y, Zhang X, Xu H, Zhang F, Zhang X, Yan Y, He L and Liu J. 2022. Isolation of lipopeptide antibiotics from *Bacillus siamensis*: a potential biocontrol agent for *Fusarium graminearum*. *Can J Microbiol*., **68(6)**: 403-11.

Hutchings MI, Truman AW and Wilkinson B. 2019. Antibiotics: past, present and future. *Current Opinion in Microbiology*., **51**:72-80.

Iswanti W, Ekawidyani KR, Asmarinah, Budijanto S and Abdullah M. 2024. The Effect of Anthocyanins Black Rice Bran Extract (ABRiBE) on Colorectal Cancer Cell Proliferation and ABCA1 Gene Expression in the HT-29 CeLL Line. *Jordan J Biol Sci*., **17(1): 197-205.**

Jakubczyk D and Dussart F. 2020. Selected fungal natural products with antimicrobial properties. *Molecules*., **25(4)**: 911.

Janek T, Krasowska A, Czyznikowska Z and Łukaszewicz M. 2018. Trehalose lipid biosurfactant reduces adhesion of microbial pathogens to polystyrene and silicone surfaces: An experimental and computational approach. *Front Microbiol*., **9**: 2441.

Jimoh AA, Booysen E, Van Zyl L and Trindade M. 2023. Do biosurfactants as anti-biofilm agents have a future in industrial water systems?. *Front Bioeng Biotechnol*., **11**: 1244595.

Kaur S and Kaur R. 2019. Biosurfactant from *Lactobacillus* sp. as an antibiofilm agent. *Biotechnologia*., **100(3)**: 335-43.

Kiran GS, Priyadharsini S, Sajayan A, Priyadharsini GB, Poulose N and Selvin J. 2017. Production of lipopeptide biosurfactant by a marine *Nesterenkonia* sp. and its application in food industry. *Front Microbiol*., **8**: 1138.

Kubicki S, Bollinger A, Katzke N, Jaeger KE, Loeschcke A, Thies S. 2019. Marine biosurfactants: biosynthesis, structural diversity, and biotechnological applications. *Mar Drugs*., **17(7)**: 408.

Kulakovskaia EV, Kulakovskaia TV, Golubev VI, Shashkov AS, Grachev AA and Nifant'ev NE. 2007. Fungicidal activity of cellobiose lipids from cultural fluid of yeast *Cryptococcus humicola* and *Pseudozyma fusiformata*. *Bioorg Khim*., **33(1)**: 167-71.

Kumar, Ajay, Sandeep Kumar Singh, Chandra Kant, Hariom Verma, Dharmendra Kumar, Prem Pratap Singh, Arpan Modi et al. 2021. Microbial biosurfactant: a new frontier for sustainable agriculture and pharmaceutical industries. Antioxidants., 10(9): 1472.

Lin S, Li X, Zhang Y, Zhang W, Shu G, Li H, Xu F, Lin J and Fu H. 2023. Rhamnolipid micelles assist azithromycin in efficiently disrupting *Staphylococcus aureus* biofilms and impeding their re-formation. *Int J Nanomed*., **18**: 7403-15.

Liu X, Shu Q, Chen Q, Pang X, Wu Y, Zhou W, Wu Y, Niu J and Zhang X. 2020. Antibacterial efficacy and mechanism of mannosylerythritol lipids-A on listeria monocytogenes. *Molecules*., **25(20)**: 4857.

Lourenco M, Duarte N and Ribeiro IAC. 2024. Exploring biosurfactants as antimicrobial approaches. *Pharmaceuticals*., **17(9)**:1239.

Manan NA, Jusoh I and Pa'ee F. 2022. Antifungal activities of *Neobalanocarpus heimii* (Cengal) heartwood extracts on *Trametes versicolor* and *Coniophora puteana*. *Journal of Tropical Biodiversity and Biotechnology*., **7(3):** jtbb69942.

McAllister JT, Lennertz L and Atencio Mojica Z. 2022. Mapping a discipline: A guide to using vosviewer for bibliometric and visual analysis. *Science & Technology Libraries*., **41(3)**: 319-48.

Mohamed EH, Abdel-Hafez SM, Soliman MM, Alotaibi SH, Alkhedaide A and Mostafa MA. 2020. Characterization and identification of methicillin-resistant *Staphylococcus aureus* (MRSA) producing biofilm: Impacts of garlic extract and *Lactobacillus* Biosurfactants. *Biomed Pharmacol J*., **13(3)**:1103-12.

Moldes AB, Rodriguez-Lopez L, Rincon-Fontan M, Lopez-Prieto A, Vecino X and Cruz JM. 2021. Synthetic and bio-derived surfactants versus microbial biosurfactants in the cosmetic industry: An overview. *Int J Mol Sci*., **22(5)**: 2371.

Morais IMC, Cordeiro AL, Teixeira GS, Domingues VS, Nardi RMD, Monteiro AS, Alves RJ, Siqueira EP and Santos VL. 2017. Biological and physicochemical properties of biosurfactants produced by *Lactobacillus jensenii* P6A and *Lactobacillus gasseri* P65. *Microb Cell Fact*., **16(1)**: 155.

Mouafo HT, Sokamte AT, Manet L, Mbarga AJM, Nadezdha S, Devappa S and Mbawala A. 2023. Biofilm inhibition, antibacterial and antiadhesive properties of a novel biosurfactant from *Lactobacillus paracasei* N2 against multi-antibiotics-resistant pathogens isolated from braised fish. *Fermentation*., **9(7)**: 646.

Nataraj BH, Ramesh C and Mallappa RH. 2021. Functional group characterization of lactic bacterial biosurfactants and evaluation of antagonistic actions against clinical isolates of methicillin-resistant *Staphylococcus aureus*. *Lett Appl Microbiol*., **73(3)**: 372-82.

Ndlovu T, Rautenbach M, Vosloo JA, Khan S and Khan W. 2017. Characterisation and antimicrobial activity of biosurfactant extracts produced by *Bacillus amyloliquefaciens* and *Pseudomonas aeruginosa* isolated from a wastewater treatment plant. *AMB Express*., **7**:108.

Nunes H, Vieira IMM, Santos BLP, Silva DP and Ruzene DS. 2022. Biosurfactants produced from corncob: A bibliometric perspective of a renewable and promising substrate. *Prep Biochem Biotechnol*., **52(2)**: 123-34.

Ohadi M, Forootanfar H, Dehghannoudeh G, Eslaminejad T, Ameri A, Shakibaie M and Adeli-Sardou M. 2020. Antimicrobial, anti-biofilm, and anti-proliferative activities of lipopeptide biosurfactant produced by *Acinetobacter junii* B6. *Microb Pathog*., **138**: 103806.

Prastiyanto ME, Iswara A, Khairunnisa A, Sofyantoro F, Siregar AR, Mafiroh WU, Setiawan J, Nadifah F, Wibowo AT and Putri WA. 2024. Prevalence and antimicrobial resistance profiles of multidrug-resistant bacterial isolates from urinary tract infections in Indonesian patients: A cross-sectional study. *Clinical Infection in Practice*., **22**: 100359.

Priyono DS, Sofyantoro F, Putri WA, Septriani NI, Rabbani A and Arisuryanti T. 2023. A bibliometric analysis of Indonesian biodiversity identification through DNA barcoding research from 2004-2021. *Nat Life Sci Commun*., **22(1)**: e2023006.

Putri WA, Setiawan J, Sofyantoro F, Priyono DS, Septriani NI, Mafiroh WU, Yano Y and Wasityastuti W. 2023. Global research trends in non-alcoholic fatty liver disease. *Bratisl Med J*., **124(8)**: 590-598.

Quinn GA, Maloy AP, McClean S, Carney B and Slater JW. 2012. Lipopeptide biosurfactants from *Paenibacillus polymyxa* inhibit single and mixed species biofilms. *Biofouling*., **28(10)**: 1151-66.

Raaijmakers JM, de Bruijn I, Nybroe O and Ongena M. 2010. Natural functions of lipopeptides from *Bacillus* and *Pseudomonas*: More than surfactants and antibiotics. *FEMS Microbiol Rev*., **34(6)**: 1037-62.

Rani M, Weadge JT and Jabaji S. 2020. Isolation and characterization of biosurfactant-producing bacteria from oil well batteries with antimicrobial activities against food-borne and plant pathogens. Front Microbiol., **11**: 64.

Reddy GS, Srinivasulu K, Mahendran B and Reddy RS. 2018. Biochemical characterization of anti-microbial activity and purification of glycolipids produced by dodecanoic acid-undecyl ester. *Res J Pharm Technol*., **11(9)**: 4066-73.

Reid G, Younes JA, Van Der Mei HC, Gloor GB, Knight R and Busscher HJ. 2011. Microbiota restoration: Natural and supplemented recovery of human microbial communities. *Nat Rev Microbiol*., **9(1)**: 27-38.

Resende AHM, Farias JM, Silva DDB, Rufino RD, Luna JM, Stamford TCM and Sarubbo LA. 2019. Application of biosurfactants and chitosan in toothpaste formulation. *Colloids Surf B Biointerfaces*., **181**:77-84.

Risdian C, Mozef T and Wink J. 2019. Biosynthesis of polyketides in *Streptomyces*. *Microorg*., **7(5)**: 124.

Rodrigues L, Banat IM, Teixeira J and Oliveira R. 2006. Biosurfactants: Potential applications in medicine. *J Antimicrob Chemother.*, **57(4)**: 609-18.

Rodríguez-López L, Rincón-Fontán M, Vecino X, Cruz JM and Moldes AB. 2019. Preservative and irritant capacity of biosurfactants from different sources: A comparative study. *J Pharm Sci*., **108(7)**: 2296-304.

Rzycki M, Gladysiewicz-Kudrawiec M and Kraszewski S. 2024. Molecular guidelines for promising antimicrobial agents. *Sci Rep*., **14(1)**: 4641.

Sabarinathan D, Vanaraj S, Sathiskumar S, Poorna Chandrika S, Sivarasan G, Arumugam SS, Preethi K, Li H and Chen Q. 2021. Characterization and application of rhamnolipid from *Pseudomonas plecoglossicida* BP03. *Lett Appl Microbiol*., **72(3)**: 251-62.

Saleh D, Jarry J, Rani M, Aliferis KA, Seguin P and Jabaji SH. 2019. Diversity, distribution and multi-functional attributes of bacterial communities associated with the rhizosphere and endosphere of timothy (*Phleum pratense* L.). *J Appl Microbiol*., **127(3)**: 794-811.

Sambanthamoorthy K, Feng X, Patel R, Patel S and Paranavitana C. 2014. Antimicrobial and antibiofilm potential of biosurfactants isolated from lactobacilli against multi-drug-resistant pathogens. *BMC Microbiol.*, **14**: 197.

Sarethy IP, Bhatia N and Maheshwari N. 2015. Antibacterial activity of plant biosurfactant extract from *Sapindus mukorossi* and in silico evaluation of its bioactivity. *Int J Pharmcy Pharm Sci*., **7(10)**: 419-21.

Sarubbo, Leonie A., C. Silva Maria da Gloria, Italo José B. Durval, Káren Gercyane O. Bezerra, Beatriz G. Ribeiro, Ivison A. Silva, Matthew S. Twigg, and Ibrahim M. Banat. 2022. Biosurfactants: Production, properties, applications, trends, and general perspectives. Biochemical Engineering Journal., 181: 108377.

Sen S, Borah SN, Bora A and Deka S. 2017. Production, characterization, and antifungal activity of a biosurfactant produced by *Rhodotorula babjevae* YS3. *Microb Cell Fact*., **16(1)**: 95.

Setiawan J, Rizal DM, Sofyantoro F, Priyono DS, Septriani NI, Mafiroh WU, Takenori K, Takashi M and Putri WA. 2024. Bibliometric analysis of organoid in regenerative medicine-related research worldwide over two decades (2002-2022). *Regen Med*., **19(3)**: 119-133.

Sharaf M, Sewid AH, Hamouda HI, Elharrif MG, El-Demerdash AS, Alharthi A, Hashim N, Hamad AA, Selim S, Alkhalifah DHM, Hozzein WN, Abdalla M and Saber T. 2022. Rhamnolipid-coated iron oxide nanoparticles as a novel multitarget candidate against major foodborne E. *coli* serotypes and methicillin-resistant S. *aureus*. *Microbiol Spectr*., **10(4)**: e0025022.

Shu Q, Lou H, Wei T, Liu X and Chen Q. 2021. Contributions of glycolipid biosurfactants and glycolipid-modified materials to antimicrobial strategy: A review. *Pharmaceutics.*, **13(2)**: 1-22.

Shu Q, Wei T, Lu H, Niu Y and Chen Q. 2020. Mannosylerythritol lipids: dual inhibitory modes against *Staphylococcus aureus* through membrane-mediated apoptosis and biofilm disruption. *Appl Microbiol Biotechnol*., **104(11)**: 5053-64.

Singh A, Van Hamme JD and Ward OP. 2007. Surfactants in microbiology and biotechnology: Part 2. Application aspects. *Biotechnol Adv*., **25(1)**: 99-121.

Singh P and Cameotra SS. 2004. Potential applications of microbial surfactants in biomedical sciences. *Trends Biotechnol*., **22(3)**: 142-6.

Sofyantoro F, Frediansyah A, Priyono DS, Putri WA, Septriani NI, Wijayanti N, Ramadaningrum WA, Turkistani SA, Garout M, Aljedah M, Al Shammari BR and Alwashmi ASS. 2023. Growth in chikungunya virus-related research in ASEAN and South Asian countries from 1967 to 2022 following disease emergence: a bibliometric and graphical analysis. *Global Health*., **19(1)**: 9.

Sofyantoro F, Kusuma HI, Vento S, Rademaker M and Frediansyah A. 2022. Global research profile on monkeypox-related literature (1962-2022): A bibliometric analysis. *Narra J*., **2(3)**: e96.

Sofyantoro F, Yudha DS, Lischer K, Nuringtyas TR, Putri WA, Kusuma WA, Purwestri YA and Swasono RT. 2022. Bibliometric analysis of literature in snake venom-related research worldwide (1933-2022). *Animals*., **12(16)**: 2058.

TechSci Research. 2023. India biosurfactants market by type (glycolipids, alkyl polyglucosides, methyl ethyl sulfonates, sucrose esters, others), by application (personal care, food processing, oil field, chemicals, textiles, others), by region, competition, forecast and opprtunities 2019-2029. Available from: https://www.techsciresearch.com/report/india-biosurfactants-market/1786.html.

Thomas L, Larroche C and Pandey A. 2013. Current developments in solid-state fermentation. *Biochem Eng* J., **81**: 146-61.

Tsuji M, Nair MS, Masuda K, Castagna C, Chong Z, Darling TL, Seehra K, Hwang Y, Ribeiro AL, Ferreira GM, Corredor L, Coelho-Dos-Reis JGA, Tsuji Y, Mori M, Boon ACM, Diamond MS, Huang Y and Ho DD. 2023. An immunostimulatory glycolipid that blocks SARS-CoV-2, RSV, and influenza infections in vivo. *Nat Commun*., **14(1)**: 3959.

Uruén C, Chopo-Escuin G, Tommassen J, Mainar-Jaime RC and Arenas J. 2020. Biofilms as promoters of bacterial antibiotic resistance and tolerance. *Antibiotics (Basel)*., **10(1)**.

Van Hamme JD, Singh A and Ward OP. 2006. Physiological aspects. Part 1 in a series of papers devoted to surfactants in microbiology and biotechnology. *Biotechnol Adv*., **24(6)**: 604-20.

Vazquez L, Teixeira da Silva Ferreira A, Cavalcante FS, Garcia IJP, dos Santos KRN, Barbosa LADO, Almeida MDS, Mignaco JA and Fontes CFL. 2018. Properties of novel surfactin-derived biosurfactants obtained through solid-phase synthesis. *J Pept Sci*., **24(11)**: e3129.

Vecino X, Rodríguez-López L, Ferreira D, Cruz JM, Moldes AB and Rodrigues LR. 2018. Bioactivity of glycolipopeptide cell-bound biosurfactants against skin pathogens. *Int J Biol Macromol*., **109**: 971-9.

Vieira IMM, Santos BLP, Ruzene DS and Silva DP. 2021. An overview of current research a developments in biosurfactants. *J Ind Eng Chem*., **100**: 1-18.

Villela H, Modolon F, Schultz J, Delgadillo-Ordoñez N, Carvalho S, Soriano AU and Peixoto RS. 2023. Genome analysis of a coral-associated bacterial consortium highlights complementary hydrocarbon degradation ability and other beneficial mechanisms for the host. *Sci Rep*., **13(12273)**: 1-14.

Wang Y, Zhang C, Liang J, Wu L, Gao W and Jiang J. 2020. Iturin a extracted from *Bacillus subtilis* WL-2 affects phytophthora infestans via cell structure disruption, oxidative stress, and energy supply dysfunction. *Front Microbiol*., **11**: 536083.

Yaraguppi DA, Bagewadi ZK, Patil NR and Mantri N. 2023. Iturin: A promising cyclic lipopeptide with diverse applications. *Biomolecules*., **13(10)**: 1515.

Zhao A, Sun J and Liu Y. 2023. Understanding bacterial biofilms: from definition to treatment strategies. *Front Cell Infect Microbiol*., **13**: 1137947.

Supplementary 1. Antimicrobial activities of biosurfactants produced by microorganisms.

Producer microorganism	Biosurfactant class	Biosurfactant type	Antimicrobial activity	Reference
Bacillus amyloliquefaciens	Lipopeptides		*Agrobacterium tumefaciens*	Abdallah *et al*., 2018
Bacillus alveayuensis		Mixture of surfactins, iturins, and fengycins	*Desulfovibrio marinus*	Argentin *et al*., 2023
Bacillus subtilis		Iturin A	*Phytophthora infestans*	Wang *et al*., 2020
Serratia marcescens		Serrawettin	*Pseudomonas aeruginosa*, methicillin-resistant *Staphylococcus aureus*, *Cryptococcus neoformans*	Clements *et al*., 2019
Pseudomonas aeruginosa	Glycolipids	Rhamnolipids	Bacteria: *Serratia marcescens*, *Enterobacter aerogenes*, *Klebsiella pneumoniae*, *Staphylococcus aureus*, *Staphylococcus epidermidis*, *Bacillus subtilis*, and phytopathogenic fungal species: *Chaetonium globosum*, *Penicillium funiculosum*, *Gliocadium virens* and *Fusarium solani*	Haba *et al*., 2003
Candida tropicalis		Sophorolipids	*Escherichia coli*, *Listeria monocytogenes* and *Staphylococcus aureus*	Ankulkar *et al*., 2019
Rhodococcus fascians		Trehalose lipid	*Vibrio harveyi* and *Proteus vulgaris*	Janek *et al*., 2018
Pseudozyma aphidis		Mannosylerythritol lipids-A	*Listeria monocytogenes*	Liu *et al*., 2020
Cryptococcus humicola and *Pseudozyma fusiformata*		Cellobiose lipids	pathogenic *Cryptococcus* and *Candida* species	Kulakovskaia *et al*., 2007
Streptomyces	Polyketides		Pathogenic fungi, various bacteria	Risdian *et al*., 2019

Supplementary 2. Antimicrobial activities of biosurfactants produced by plants.

Producer plants	Biosurfactant class	Biosurfactant type	Antimicrobial activity	Reference
Chenopodium quinoa	Saponins			Bezerra *et al*., 2021
Glycine max	Saponins			Bezerra *et al*., 2021
Malphiguia ermaginata	Saponins			Bezerra *et al*., 2021
Quillaja saponaria	Saponins		*Asaia spp.* biofilm	Antolak *et al*., 2018
Chenopodium quinoa Wild.	Saponins		*Staphylococcus aureus, Staphylococcus epidermidis, B. aureus, S. enteritidis, P. aeruginosa, L. ivanovii*	Dong *et al*., 2020
Sapindus mukorossi fruits	Saponins	Sapindoside B, Sapinmusaponin A, Sapinmusaponin F, Sapinmusaponin N	*B. subtilis, B. linens, M. luteus, S. epidermidis, E. coli, P. fluorescens*	Sarethy *et al*., 2015

Supplementary 3. Antibiofilm properties of biosurfactants

Producer microorganism	Biosurfactant class	Biosurfactant type	Antibiofilm activity	Reference
Endophyte *Burkholderia* sp.	Glycolipid		*Staphylococcus aureus*	AA *et al*., 2020
Paenibacillus polymyxa	Lipopeptide	Polymyxin D1 Surfactins	*Bacillus subtilis, Micrococcus luteus, Pseudomonas aeruginosa,* *S. aureus, Streptococcus bovis*.	Quinn *et al*., 2012
Nesterenkonia sp.	Lipopeptide		*Staphylococcus aureus*	Kiran *et al*., 2017
Lactobacillus jensenii P_{6A} and *Lactobacillus* *gasseri* P_{65}	Unclassified		*Staphylococcus saprophyticus, Enterobacter aerogenes* and *Klebsiella pneumoniae*	Morais *et al*., 2017
Bacillus subtilis	Lipopeptide		*Achromobacter xylosoxidans,* *Alcaligenes faecalis, Pseudomonas alcaligenes*	de Souza Freitas *et al*., 2020
Acinetobacter junii	Lipopeptide		*Proteus mirabilis, S. aureus,* *Pseudomonas aeruginosa*	Ohadi *et al*., 2020
Pseudozyma aphidis	Glycolipid	Mannosylerythritol lipids	*S. aureus*	Shu *et al*., 2020
Bacillus velezensis	Lipopeptide	Surfactin	*P. aeruginosa,* *E. coli,* *K. pneumoniae,* *S. aureus*	Ali *et al*., 2022
Shewanella algae	Glycolipid		*Bacillus cereus, Streptococcus pneumoniae, Pseudomonas aeruginosa, Escherichia coli, K. pneumoniae, Acinetobacter sp.*	Gharaei *et al*., 2022
Lactobacillus acidophilus	Unclassified		*Chromobacterium violaceum,* *Serratia marcescens, Pseudomonas aeruginosa*	Adnan *et al*., 2023
Bacillus subtilis B. vallismortis	Lipopeptides	Iturin Fengycin Surfactin	*Malassezia furfur*	Da Silva *et al*., 2021
Pseudomonas plecoglossicida	Glycolipid	Rhamnolipid	*S. aureus,* *B. subtilis, Aeromonas hydrophila*	Sabarinathan *et al*., 2021
Bacillus amyloliquefaciens	Unclassified		*Acinetobacter baumannii*	Amer *et al*., 2023
P. aeruginosa	Glycolipid	Rhamnolipid	*Baumannii,* *Enterococcus faecium*	Firdose *et al*., 2023
Lactobacillus paracasei		glycolipoprotein	*E. coli,* *S. aureus,* *Salmonella enteritidis, P. aeruginosa, Yersinia enterolitica, Proteus mirabilis,* *K. pneumoniae*	Mouafo *et al*., 2023

Supplementary 4. Development of Biosurfactant formulation strategy

Formulation strategy	Antimicrobial activity	Reference
Liposomes containing biosurfactants	*S. aureus*	Giordani *et al*., 2019
Toothpaste with biosurfactant and chitosan or sodium fluoride	*Streptococcus mutans*	Resende *et al*., 2019
Garlic extract with biosurfactant	*S. aureus*	Mohamed *et al*., 2020
Chitosan-based nanoparticle	*Helicobacter pylori*	Arif *et al*., 2021
Lipopeptides and glycolipids combination	*albicans*	Ceresa *et al*., 2021
	Staphylococcus spp.	
Usnic acid-loaded Rhamnolipid vesicle	*S. aureus*	Falakaflaki *et al*., 2022
Rhamnolipid-coated iron oxide nanoparticles	*coli*	Sharaf *et al*., 2022
	S. aureus	
Glycolipid and antibiotics combination	*S. aureus*	Amirinejad *et al*., 2023
	A. baumannii	
Biosurfactant nanoemulsion	*E. coli*	Haddaji *et al*., 2023
	S. aureus	