



Biosurfactants aided bioremediation mechanisms: A mini-review

Bami, M. S., Estabragh, M. A. R., Ohadi, M., Banat, I. M., & Dehghannoudeh, G. (2022). Biosurfactants aided bioremediation mechanisms: A mini-review. *Soil and Sediment Contamination: An International Journal*, 31(7), 801-817. Advance online publication. <https://doi.org/10.1080/15320383.2021.2016603>

[Link to publication record in Ulster University Research Portal](#)

Published in:

Soil and Sediment Contamination: An International Journal

Publication Status:

Published online: 10/02/2022

DOI:

[10.1080/15320383.2021.2016603](https://doi.org/10.1080/15320383.2021.2016603)

Document Version

Author Accepted version

General rights

Copyright for the publications made accessible via Ulster University's Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The Research Portal is Ulster University's institutional repository that provides access to Ulster's research outputs. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact pure-support@ulster.ac.uk.

1 **Biosurfactants aided Bioremediation mechanisms: a mini-review**

2 Marzieh Sajadi Bami^a, Mohammad Amin Raeisi Estabragh^b, Mandana Ohadi^c, Ibrahim M
3 Banat^d, Gholamreza Dehghannoudeh^{c*}

4 *^a Student research committee, Kerman University of Medical Sciences, Kerman, Iran.*

5 *^b Department of Pharmaceutics, Faculty of Pharmacy, Kerman University of Medical
6 Sciences, Kerman, Iran*

7 *^c Pharmaceutics Research Center, Institute of Neuropharmacology, Kerman University of
8 Medical Sciences, Kerman, Iran*

9 *^d School of Biomedical Sciences, Faculty of Life & Health Sciences, University of Ulster,
10 Coleraine BT52 1SA, Northern Ireland, UK*

11 -----

12 *Corresponding author:

13 Tel.: +98 3431325014, Fax: +98 3431325003. E-mail: ghr_dehghan@kmu.ac.ir,

14 gholamreza.dehghannoudeh@utoronto.ca. (G. Dehghannoudeh)

15

16 **Abstract**

17 Biosurfactants can be used for bioremediation as amphiphilic compounds that have shown
18 good tolerance to changes in temperature, salt concentration, pH, and other environmental
19 factors. They have received increased attention in bioremediation because they are
20 biodegradable and do not generate any secondary contaminants. Biosurfactants are used to
21 remove organic molecules for example hydrocarbon contaminants through various
22 mechanisms such as surface tension reduction, emulsification, and micelle formation. They can
23 also play a role in removing heavy metals by increasing contact with the surface of heavy metal
24 deposits and forming complexes and micelle formation. In this review, we focus on the role of
25 biosurfactants in improving the efficacy of bioremediation.

26 Keywords: Bioremediation; Biosurfactants; Oil pollution; Emulsification, Biodegradation

27

28 **1. Introduction**

29 The release of potentially hazardous organic and inorganic pollutants into the ecosystem has
30 been a topic of interest for years (1). Organic compounds and heavy metals are, usually present
31 in the soil and high concentrations the inorganic contaminants are known to have the greatest
32 risk to humans (2). The accumulation of non-degradable pollutants as heavy metals in
33 biological systems would ultimately lead to the contamination of the entire food chain (3). In
34 2015 it was reported that pollution-induced diseases resulted in an estimated 9 million
35 premature deaths representing 16% of all deaths in the world (4). The physical approaches of
36 bioremediation are mainly method of eliminating or degrading mainly organic pollutants
37 present in the soil by different methods including physical techniques such as soil replacement
38 processes, landfill barrier methods, and thermal desorption approaches (5). Chemical cleanup
39 meanwhile consist mainly of soil solidification-stabilization, leaching, and oxidation-reduction
40 processing. The solidification-stabilization technique could establish long-term stability of
41 pollutants in contaminated media (6). Physical and chemical techniques of remediation/cleanup
42 are usually costly and do not result in complete pollutants removal and often require
43 management of a significant amount of harmful waste generated (7).

44 Alternative bioremediation strategies to eliminate pollution are considered as relatively new
45 sustainable recent approaches. There are three types/approaches for bioremediation:
46 phytoremediation, animal remediation and microbial remediation (8). Phytoremediation, a
47 practical, cheap and environmentally friendly rehabilitation strategy, is a bioremediation
48 technology that involves plants to remove either organic and inorganic contaminants,
49 particularly from the soil environment (9). Animal remediation is also used widely to remedy
50 soil and water contamination at specific locations (10). Microbial remediation process in
51 comparison is mainly carried out by microorganisms or parts thereof to remove or clean up
52 contaminants through their effective degradation and/or enhancing their bioavailability and

53 breakdown. This process is the main approach for removing many environmental pollutants,
54 such as products from the petroleum industry (11). In some experiments, the polluted
55 hydrocarbon soils were augmented with biosurfactants producing bacterial species which
56 resulted in enhance hydrocarbons degradation (2, 12, 13). Plants, animals, and microbes are
57 known to synthesize biosurfactants (14). Biosurfactants are known as amphiphilic compounds
58 consisting of hydrophilic and hydrophobic moieties (15)) . This composition gives them
59 surface-active properties, including reduction of surface and interfacial tension in aqueous
60 solutions and mixtures of hydrocarbons (2, 16). This indicates that biosurfactants can be used
61 to enhance bioremediation processes. Hence, in this review, we focus on the above issues
62 through a discussion bioremediation with biosurfactants and their mechanism.

63 **2. Pollution**

64 Water and soil are the main recipients for different pollutants that influence their quality,
65 nature, and performance. Hydrocarbon pollutants may include alkanes, aromatic compounds,
66 chlorinated hydrocarbons, heterocyclic nitrogen, and nitroaromatics (17). Metal pollution in
67 the ecosystem has also increased as a result of increased industrial activity. Heavy metals are
68 present in soil and are known to be the inorganic pollutants with the greatest significant hazard
69 to humans (18, 19). Metal toxicity is not only related to the exposure level but also to the
70 metallic chemical species involved, which has an effect on stability and bioavailability within
71 the ecosystem (20). Due to the propensity of such substances to bioaccumulation, they impose
72 a considerable risk for food safety and all living organism (21, 22).

73 Hydrocarbons are the most common organic contaminant in soil and water which are of
74 growing concerns (11). Numerous oil spills repeatedly displayed the hazard effects
75 hydrocarbons have on the environment. Oil pollution therefore needs solutions that are quick
76 and economical (23). The persistence of organic polluting compounds within the natural
77 environment depends on many factors, including chemical composition, distribution, and

78 concentration (24). In the event of an oil spill, physicochemical remedies are usually applied;
79 however, these procedures are very costly and more strategies may be required depending on
80 the chemical agents selected as surfactants or catalysts (25). Chemical remediation requires the
81 addition of chemical compounds to degrade pollutants or turn them into substances that are less
82 hazardous to the environment. Oxidation, reduction, polymerization, and precipitation are the
83 most widely used methods in this process (26).

84 Conventional physical remedies that separate/isolate soil and pollutants without chemical
85 destruction or modifications of the oils are also common. Many of the petroleum products are
86 trapped in the soil matrix, thereby reducing each remediation method performance. Biological
87 processes on the other hand offers efficient remediation methods, as they combine efficiency
88 and cost-effectiveness. Among many novel strategies, bioremediation consistently emerges as
89 the least aggressive and often the most suitable method for maintaining the ecological balance
90 (27).

91 **3. Bioremediation methods**

92 The use of biological processes to remove or transform pollutants in the environment to either
93 safe levels or to turn pollutants into acceptable forms is known as bioremediation (8, 20). The
94 definition involves biodegradation, which relates to the transformation or detoxification of
95 contaminants partially or completely by biological systems (28). Bioremediation is therefore a
96 method that improves the effectiveness of the natural biodegradation process (29). This
97 technique involves low-technology and is generally more economical and can often be carried
98 out on-site or *in situ* (30, 31). The purpose of bioremediation is to reduce contamination levels
99 to less toxic or safe levels, compared to the limits set by regulatory agencies or, preferably,
100 complete mineralization to water and carbon dioxide (28). Bioremediation is also beneficial
101 because of its environmentally sustainable nature, as it does not involve the introduction of
102 foreign or hazardous chemicals to the polluted site. Environmental sustainability is as a result

103 of using natural reproducible additives that do not entail any damage to the natural ecosystem
104 that often results from chemical and physical remediation methods. Bioremediation enables
105 biological organisms to degrade toxic hydrocarbons into simple compounds that do not pose
106 risk to human health and minimizes the need to eliminate and transfer harmful substances to
107 another location (32). Biosurfactants producing bacterial species were shown to enhance
108 hydrocarbon degradation through increased hydrocarbon removal compared to common
109 chemical surfactants uses (12, 33). Therefore, biosurfactants applications are attractive in
110 bioremediation processes(34).

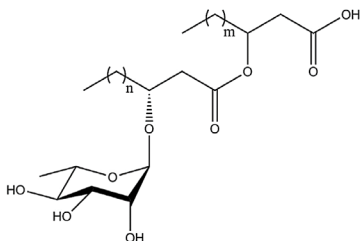
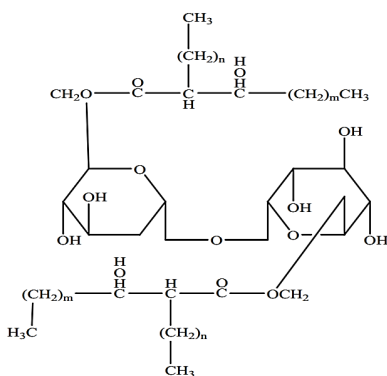
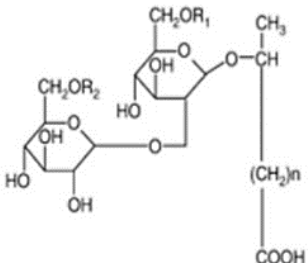
111 4. **Biosurfactants properties and types**

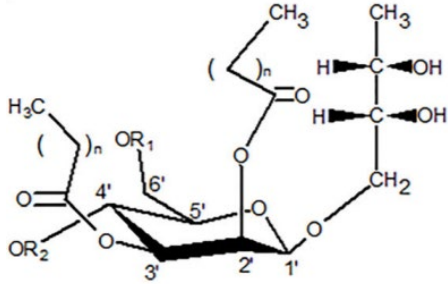
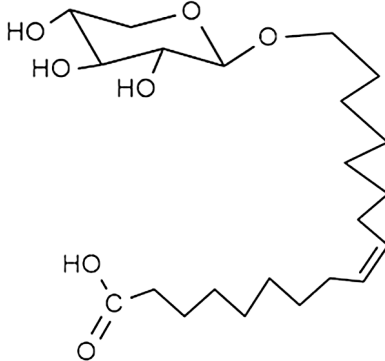
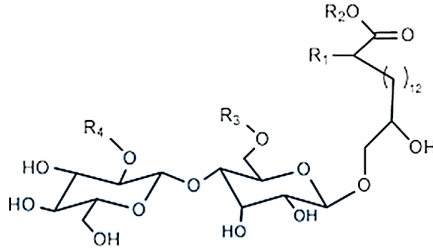
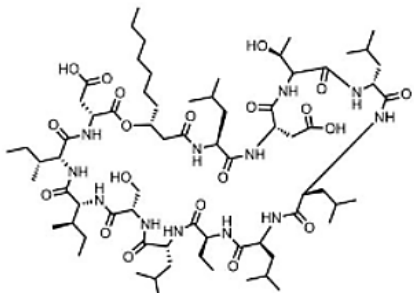
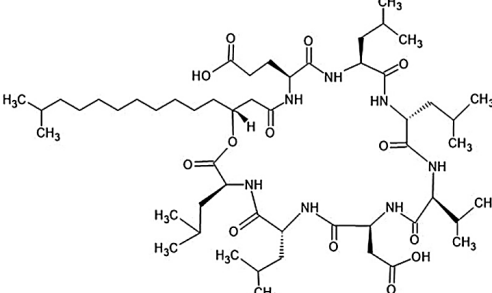
112 Biosurfactants are amphiphilic compounds containing both lipophilic and hydrophilic groups.
113 This structure gives them surface-active features such as surface and interfacial tension
114 reductions in mixtures of waters and hydrocarbon (16). Plants, animals and microbes are
115 reported to synthesize biosurfactants (14). These can have lower critical micelle concentration
116 (CMC) values than synthetic surfactants which improves their performance in different
117 applications. Microbial biosurfactants are divided into two main groups high molecular weight
118 (HMW) polymeric compounds, e.g. polysaccharides, proteins or combined lipoprotein and
119 lipopolysaccharide types and low molecular weight (LMW), e.g. lipopeptides and glycolipids
120 (35). HMW biosurfactants can adhere very firmly to different surfaces and act as bio
121 emulsifiers. LMW biosurfactants such as rhamnolipids and sophorolipids that are disaccharides
122 with long chain acetylated fatty acids or hydroxyl fatty acids. They significantly reduce surface
123 and interfacial tension (36).

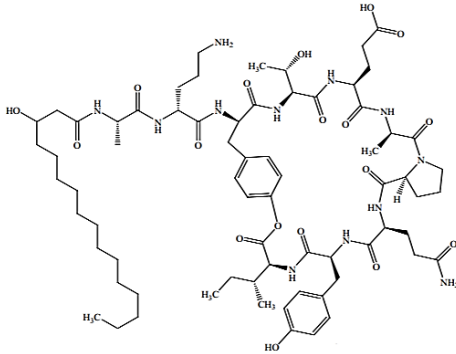
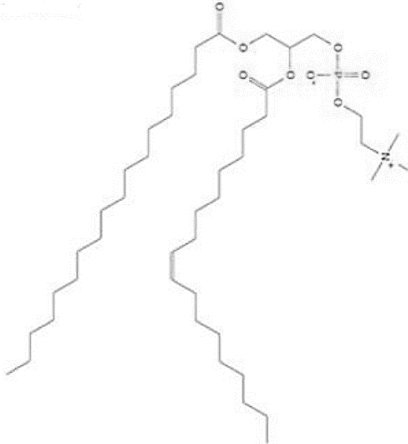
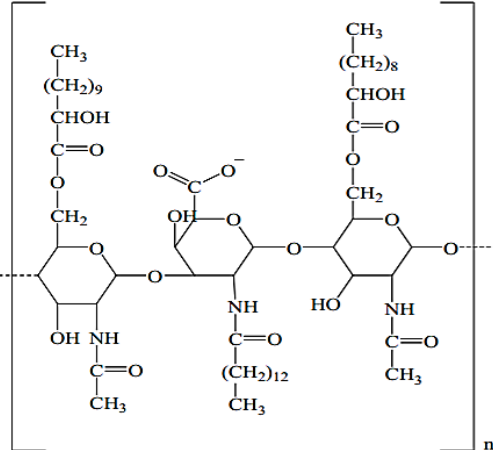
124 Unlike chemically synthesized surfactants, which are classified according to the nature of their
125 polar group, biosurfactants are categorized mainly by their chemical composition and their
126 microbial origin. In general, their structure includes a hydrophilic moiety consisting of amino

127 acids or peptides, anions or cations; mono-, di-, or polysaccharides; and a hydrophobic moiety
 128 consisting of unsaturated and saturated fatty acids (37, 38). Glycolipids are the most known
 129 biosurfactants. They are conjugates of carbohydrates and fatty acids. The linkage is by means
 130 of either an ether or an ester group (39, 40). Lipopeptides can also be classified as biosurfactants
 131 (41). A summary of the classification of biosurfactants and their structure is shown in Table 1.

132 Table 1. Classification of biosurfactants and their structure

Biosurfactant types	Biosurfactants subtypes	Chemical structure example	Reference
	Rhamnolipids		(42)
Glycolipids			(43, 44)
	Sophorolipids		(45)

	Mannosylerythritol Lipids		
	Xylolipids		(47)
	Cellobiose lipids		(47)
Lipopeptides			(48)
	Surfactin		(49)

	Fengycin		(44)
Fatty Acids and Phospholipids	Phospholipids		(50)
Polymeric Biosurfactant	Emulsan		(44)

133

134 **4-1. Glycolipid biosurfactants**

135 **4-1-1. Rhamnolipids**

136 Rhamnolipids are glycolipid biosurfactants, mainly produced by *Pseudomonas aeruginosa*

137 which are well known for their potential industrial, bioremediation and environmental uses (51,

138 52). They are composed of one or two rhamnose sugar groups linked to one or two fatty acid
139 chain of mainly 10-14 carbon atoms, forming mono or di-rhamnolipid molecules (53).

140 **4-1-2. Trehalolipids**

141 Trehalolipids are disaccharide trehalose linked to mycolic acids. Trehalolipids from different
142 organisms differ in the size and structure of mycolic acid, the number of carbon atoms, and the
143 degree of unsaturation (54). Trehalolipids are produced by different species of *Mycobacterium*,
144 *Nocardia*, and *Corynebacterium*. For example, trehalose dimycolate produced by *Rhodococcus*
145 *erythropolis* (43, 55-57).

146 **4-1-3. Sophorolipids**

147 Sophorolipids are extra cellular glycolipids consist of a dimeric carbohydrate sophorose linked
148 to a long-chain hydroxy fatty acid by a glycosidic bond. These biosurfactants are a mixture of
149 at least six to nine different congeners, and showed application related to the oil bioremediation
150 (58, 59). The purified sophorolipids were more surface active, less water soluble and showed
151 stronger cytotoxic effects. Although, sophorolipids can lower surface and interfacial tension,
152 they are not effective emulsifying agents (60). Sophorolipids are produced mainly by yeasts
153 such as *Torulopsis bombicola*, *T. petrophilum* and *T. apicola* (61-63).

154 **4-1-4. Mannosylerythritol Lipids**

155 biosurfactants containing mannose, erythritol, and two fatty acid chains are known as
156 mannosylerythritol lipids. These glycolipids are centered around the disaccharide
157 mannosylerythritol. The 2' and 3' positions of two fatty acids are linked to mannose by ester
158 bonds and a bond at the 1' position links erythritol to mannose (64, 65).

159 **4-1-5. Xylolipids**

160 A xylolipid is a glycolipid biosurfactant with a xylose head and fatty acid tails. The bacteria
161 that produce xylolipids are usually lactic acid bacteria (66). Although a few yeast species such
162 as *Pichia caribbica* are reported to be able to synthesize xylolipids. In Joshi-Navare *et al*,

163 research xylolipids as biosurfactants can reduce the surface tension to 35.9 mNm^{-1} with a CMC
164 of 1 mgL^{-1} (67).

165 **4-1-6. Cellobiose lipids**

166 Cellobiose lipids are a group of biosurfactants produced by microbes as secondary metabolites.
167 It is usually produced as a mixture of different acylated low molecular weight D-glucolipids,
168 linked to a hydroxyl palmitic acid via their ω -hydroxyl groups (68, 69). Cellobiose lipids were
169 produced by *Cryptococcus humicola* JCM 1461 and the structure of main product was 16-O-
170 (2'',3'',4'',6'-tetra -O-acetyl- β -cellobiosyl)-2-hydroxyhexadecanoic acid. The CMC was
171 $3.3 \times 10^5 \text{ M}$ and $4.1 \times 10^4 \text{ M}$ in pH 4.0 and 7.0 respectively (69).

172 **4-2. Lipopeptides biosurfactants**

173 The group of Lipopeptide/lipoproteins presents a heterogeneous class of biologically active
174 peptides and most of them are known to possess antimicrobial activity. Arthrofactin (AF) and
175 surfactin (SF) are the most effective cyclic lipopeptide biosurfactants ever reported (49, 70).

176 **4-2-1. Arthrofactin**

177 *Arthrobacter* and *Actinomyces* and *Streptomyces* produced arthrofactin, a lipopeptide
178 biosurfactant type (71). The surface and interfacial behavior of arthrofactin is noteworthy as
179 this cyclic lipopeptide (at a concentration of $100 \mu\text{M}$) can reduce the surface tension of water
180 from 72 to 24 mNm^{-1} (72). Effects on biofilm formation, in addition to a wide range of
181 industrial applications relevant for medical applications were reported for arthrofactin (72, 73).

182 **4-2-2. Surfactin**

183 Surfactant is a cyclic lipopeptide consisting of a hydrophobic tail that is thirteen to fifteen
184 carbons long chain with seven amino acids produced by *Bacillus subtilis* is the most effective
185 biosurfactant with low toxicity (74, 75). The amphiphilic nature helps surfactin to exist and
186 function in both hydrophobic and hydrophilic environments. Surfactin is a commonly used
187 biosurfactant with detergents, antimicrobial, antibacterial, and antiviral properties in a variety

188 of industries and formulations of cosmetic products, and oil bioremediation (76).

189 **4-2-3. Fengycin**

190 In fengycin as cyclic lipopeptide, decapeptides are joined to a linear chain of β -fatty acid by
191 cyclization between the phenol side chain at position 3 and the C-terminus of an amino acid at
192 position 10 (77). *Bacillus* species are the primary producers of fengycin (78). It has been
193 demonstrated that fengycin readily interacts with the lipid bilayer and have antimicrobial
194 effects (79). A lipopeptide closely related to fengycin has been identified and referred to as
195 plipastatin. In fengycin and plipastatin, the Tyr position differs (80, 81).

196 **4-3. Fatty Acids, and Phospholipids biosurfactants**

197 Several bacteria and yeasts produce large quantities of fatty acid and phospholipid surfactants
198 during growth on n-alkanes. The HLB is directly related to the length of the hydrocarbon chain
199 in their structures. These are usually organisms which produce surface-active lipids when
200 growing on hydrocarbon substrates. Several different types of biosurfactants have been isolated
201 and characterized. These include glycolipids, lipopeptides, phospholipids, and neutral lipids.
202 The complex lipids all contain fatty acids and these fatty acids often have a hydroxyl function
203 on the carbon β to the carboxyl group or farther along the chain (82, 83). One of the most
204 popular phospholipid biosurfactants is produced by *Corynebacterium Lepus* (83).

205 **4-4. Polymeric biosurfactants**

206 Extracellular polymeric substances (EPSs) such as emulsan are involved in both detrimental
207 and beneficial consequences of microbial aggregates such as biofilms, flocs and biological
208 sludge. In biofouling, they are responsible for the increase of friction resistance, change of
209 surface properties such as hydrophobicity, roughness, color, etc. In bio corrosion of metals,
210 they are involved by their ability to bind metal ions. In bio weathering, they contribute by their
211 complexing properties to the dissolution of minerals. The EPSs represent a sorption site for
212 pollutants such as heavy metal ions and organic molecules (84, 85).

213 **5. Biosurfactants in bioremediation**

214 Biosurfactants can withstand high temperatures, high salt concentrations and harsh conditions
215 and remain stable. Remediation techniques using biosurfactants and microorganisms
216 generating biosurfactants help to detoxify petrolatum and heavy metals from the contaminated
217 environment (86-89). Biosurfactants produced by *Serratia marcescens* ZCF25 are lipopeptide.
218 This microorganism was isolated from oil sludge. Biosurfactants were highly stable in harsh
219 environments, reduce surface tension and have a bioremediation application (90)
220 *Stenotrophomonas* sp. S1VKR-26 produces biosurfactants that can be used for bioremediation
221 of petrolatum contamination in wastewater (91). *Bacillus cereus* UCP 1615 biosurfactant are
222 lipopeptide type with potential for oil spills remediation (92). The extracted biosurfactant from
223 *Rhodococcus erythropolis* HX-2 increase the solubility of the hydrophilic compound and
224 enhances petroleum biodegradation (93).

225 Some studies and research with regard to biosurfactants which improved the biological
226 degradation of contaminants are shown in Table 2.

227 **Table 2.** Numerous studies shown biosurfactants improved the biological degradation of contaminants.

Microorganisms	Pollutants	Biosurfactant Type	Mechanisms of Effects	Reference
<i>Bacillus</i> sp.	Zinc, lead, chromium and copper	Lipopeptide	Complex (biosurfactant–metal) formation, then the complex form micelles and mobilize (leaves the soil)	(86)
<i>Acinetobacter</i> sp. <i>Pseudomonas putida</i>	Lead, zinc and copper	Rhamnolipid	Wetting, interaction to the sediment surface and metal separation from the sediment	(94)
Isolates of KDM3, KDM 4, KDM 6	Zinc, lead and chromium	Biosurfactant (not specified)	No purpose mechanism	(95)
<i>Pseudomonas</i> sp. CQ2	Cd, Cu and Pb	Biosurfactant (not specified)	Metals complex with carboxyl functional groups in biosurfactants	(33)
<i>Achromobacter xylosoxidans</i> <i>Stenotrophomonas maltophilia</i>	Polychlorinated biphenyls	Saponin Rhamnolipid	Direct bacterial cell absorption of pollutants from the micellar core, increased mass transfer of contaminants to the aqueous phase,	(96)

			and modifying cell surface and cell lipophilicity	
<i>Saccharomyces cerevisiae</i>	Biodiesel	Mannoprotein	Emulsifying contaminant with soil particles, thereby promoting biodegradation	(97)
Mixed culture microflora	Biodiesel and diesel oil	Rhamnolipid	Increase bioavailability of organic compounds solubilized in micelles to microbial cells	(98)
<i>Achromobacter</i> sp. A-8	Petroleum	Biosurfactant (not specified)	Decreases surface tension and high performance in oil displacement	(87)
<i>Serratia</i> sp.	Hydrocarbon	Lipopeptide	Reduced surface and interfacial tension increasing hydrocarbons surface area, which makes them accessible to the microbe	(99)
<i>Bacillus cereus</i>	Oil	Lipopeptide	Increase of lipophilic substrates' bioavailability	(100)
<i>Shewanella</i> sp.	Oil	Rhamnolipid	Improving the rate of mass transfer and microbial adhesion	(88)

<i>Wickerhamomyces anomalous</i>	Crude oil	Lipopeptide	Reduction in surface tension	(101)
<i>Bacillus algicola</i> (003-Phe1), <i>Rhodococcus soli</i> (102-Na5), <i>Isophtericola chiayiensis</i> (103-Na4), and <i>Pseudalteromonas agarivorans</i> (SDRB-Py1)	Crude oil	Rhamnolipid	Increasing the emulsification of crude oil	(102)
<i>Bacillus</i> sp. and <i>Acinetobacter</i> sp.	Oil	Lipopeptide Emulsan	Micelles formation	(89)
<i>Serratia marcescens</i> UCP 1549	Burned motor oil	Lipopeptide	emulsify oil, improve water solubility and decrease the surface tension	(103)
<i>Bacillus methylotrophicus</i> UCP1616	Motor oil	Lipopeptide	Increases the surface area of the hydrocarbons and enhances the interaction of the hydrophobic contamination and the microbial cell membrane	(104)

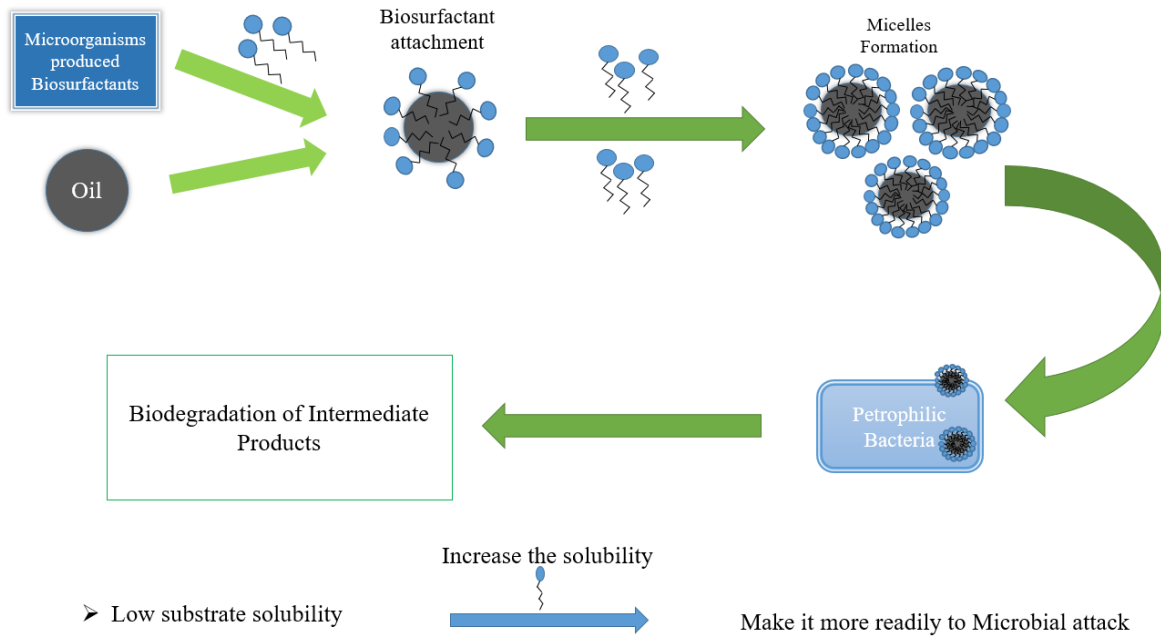
<i>Paenibacillus</i> sp. D9	Diesel and motor oil	Biosurfactant (not specified)	Increase the solubility of the hydrophobic contaminated aqueous environment, thereby improving biodegradation	(105)
<i>Acinetobacter</i> sp. Y2	Hydrocarbon	Lipopeptide	Improve the solubility and bioavailability of lipophilic compounds	(106)
<i>Bacillus stratospheric</i> strain FLU5	Motor oil	Lipopeptide	Micelles formation and increases the solubility of pollutions	(107)
<i>Staphylococcus epidermidis</i> EVR4	Diesel oil	Biosurfactant (not specified)	Oil pollutants become more soluble by biosurfactant	(108)

229 **6. Mechanism of biosurfactants in bioremediation**

230 One variable affecting the process of microbial degradation is the bioavailability of the
231 polluting compounds to the degrading bacteria (109). Biosurfactants increase the hydrophobic
232 pollutants bioavailability to microbes for biodegradation through enhancing their solubility
233 (97). One application of biosurfactants is improving the biodegradation process of insoluble
234 organic contaminations. Biosurfactant influences the rate of biodegradation of hydrocarbons
235 and increases the decomposition process through two mechanisms; by increasing the solubility
236 of petroleum hydrocarbons and by controlling the interaction between bacterial cells and
237 petroleum substances reducing the surface tension among two phases (17). Biosurfactants as
238 amphiphilic structure accumulate and form micelles in the hydrophilic environment at bulk
239 concentrations above the CMC. Micelles are thermodynamically stable structures, and micelle
240 formation is an equilibrium process. In micelle structures, hydrophobic groups of surfactants
241 contact/orients towards the hydrophobic environment and hydrophilic groups contact/orients
242 towards the aqueous phase; thus, hydrophobic contamination become dispersed and soluble in
243 the aqueous solvent. On the other hand, micelle can increase the rate of absorption of substance
244 to microbial cells (17, 107, 110).

245 Biosurfactants can enhance biodegradation of poorly soluble substances by two main processes
246 which enhance/increased bioavailability:

- 247 ➤ Improving the solubility by emulsifying hydrophobic compounds, making it more
248 accessible to microbial attack.
- 249 ➤ Facilitating transfer of hydrophobic contamination by micelle formation, providing
250 greater access to bacterial cells (17).



251 Fig.1 shown how biosurfactants can be increased bioremediation.

252 Fig.1 Mechanisms of microbial degradation of the hydrophobic compound with the aid of
 253 biosurfactants

254 Biosurfactants with complexation or surface sorption can aid heavy metal remediation. The
 255 anionic biosurfactant has a strong affinity to cationic heavy metals such as Zinc, Lead,
 256 Chromium and Copper and complexed with them, then biosurfactant–metal complex leaves
 257 the soil surfaces and form micelles. Based on this, biosurfactants can use for heavy-metal
 258 pollution remediation (33, 86, 111). Smaller micelles are more beneficial to biosurfactant
 259 diffusion in the soil, which increases the contact area with heavy metals in the soil and thus
 260 improves bioremediation performance (33).

261 7. Conclusion

262 The biosurfactants can be used as a low-cost method without the need for special equipment
 263 and in situ techniques to degrade organic contaminants such as petroleum and mobilise/collect
 264 inorganic contaminants such as heavy metals. Biosurfactants increase solubility by emulsifying
 265 hydrophobic pollution and providing greater access of microorganisms to contamination,

266 complexed with heavy metals and micelle formation, lead to the removal of contamination
267 without creating a new toxic product.

268 **8. Future prospects**

269 The use of biosurfactants is an attractive option because of its versatility, biodegradability,
270 ecological safety and environmental acceptance. Due to its higher production cost, purification
271 and low yield, biosurfactant used has limited. For produce a high yield of surfactants and lower
272 cost biosurfactants; renewable substrates, alternative purification technologies, genetic and
273 metabolic engineering tools, and statistical methods can be applied. More efforts are required
274 to evaluate biosurfactants in situ and their effect on indigenous microorganisms.

275 **Acknowledgments**

276 This article is the result of a research project approved by the Student Research Committee of
277 Kerman University of Medical Sciences No. 99001081, which was carried out with the
278 financial support of the Vice-Chancellor for Research and Technology of the University.

279

References

280
281

- 282 1. Ghafari S, Hasan M, Aroua MK. Bio-electrochemical removal of nitrate from water
283 and wastewater—a review. *Bioresource technology*. 2008;99(10):3965-74.
- 284 2. Santos DK, Resende AH, de Almeida DG, Soares da Silva RdCF, Rufino RD, Luna
285 JM, et al. *Candida lipolytica* UCP0988 biosurfactant: potential as a bioremediation agent and
286 in formulating a commercial related product. *Frontiers in Microbiology*. 2017;8:767.
- 287 3. RoyChowdhury A, Datta R, Sarkar D. Heavy metal pollution and remediation. *Green*
288 *Chem: Elsevier*; 2018. p. 359-73.
- 289 4. Landrigan PJ, Fuller R, Acosta NJ, Adeyi O, Arnold R, Baldé AB, et al. The Lancet
290 Commission on pollution and health. *The lancet*. 2018;391(10119):462-512.
- 291 5. Rahman KS, Rahman TJ, Kourkoutas Y, Petsas I, Marchant R, Banat I. Enhanced
292 bioremediation of n-alkane in petroleum sludge using bacterial consortium amended with
293 rhamnolipid and micronutrients. *Bioresource technology*. 2003;90(2):159-68.
- 294 6. Zhu D. Research on Remediation Methods of Contaminated Land and Development
295 Trend. *Environment, Resource and Ecology Journal*. 2018;2(1):15-21.
- 296 7. Azubuike CC, Chikere CB, Okpokwasili GC. Bioremediation: An Eco-friendly
297 Sustainable Technology for Environmental Management. *Bioremediation of Industrial Waste*
298 *for Environmental Safety: Springer*; 2020. p. 19-39.
- 299 8. Song X, Lin N, Yin P. Contaminated site remediation industry in China: current state
300 and future trends. *Soils*. 2015;47(1):1-7.
- 301 9. Wang L, Ji B, Hu Y, Liu R, Sun W. A review on in situ phytoremediation of mine
302 tailings. *Chemosphere*. 2017;184:594-600.
- 303 10. Yan L, Zhao W, editors. *Application Research on Soil and Water Environmental*
304 *Pollution Remediation Technology*. IOP Conference Series: Earth and Environmental
305 Science; 2019: IOP Publishing.
- 306 11. Inieke E, Michael E, Ben M. Microbial Remediation of Crude Oil Contaminated Soil
307 using Animal Waste (Chicken Droppings and Cow Dung) with Degrading Potentials. *Toxicol*
308 *Open Access*. 2018;4(135):2476-067.1000135.
- 309 12. Shan L, Gao Y, Zhang Y, Yu W, Yang Y, Shen S, et al. Fabrication and use of
310 alginate-based cryogel delivery beads loaded with urea and phosphates as potential carriers
311 for bioremediation. *Industrial & Engineering Chemistry Research*. 2016;55(28):7655-60.
- 312 13. Zhuang W-Q, Tay J-H, Maszenan A, Tay S. *Bacillus naphthovorans* sp. nov. from oil-
313 contaminated tropical marine sediments and its role in naphthalene biodegradation. *Applied*
314 *microbiology and biotechnology*. 2002;58(4):547-54.
- 315 14. Marchant R, Banat IM. Biosurfactants: a sustainable replacement for chemical
316 surfactants? *Biotechnology letters*. 2012;34(9):1597-605.
- 317 15. De Almeida DG, Soares Da Silva RdCF, Luna JM, Rufino RD, Santos VA, Banat IM,
318 et al. Biosurfactants: promising molecules for petroleum biotechnology advances. *Frontiers in*
319 *microbiology*. 2016;7:1718.
- 320 16. Santos DKF, Rufino RD, Luna JM, Santos VA, Sarubbo LA. Biosurfactants:
321 multifunctional biomolecules of the 21st century. *International journal of molecular sciences*.
322 2016;17(3):401.
- 323 17. Effendi AJ, Kardena E, Helmy Q. Biosurfactant-Enhanced Petroleum Oil
324 Bioremediation. *Microbial Action on Hydrocarbons: Springer*; 2018. p. 143-79.
- 325 18. Sarubbo L, Rocha Jr R, Luna J, Rufino R, Santos V, Banat IM. Some aspects of heavy
326 metals contamination remediation and role of biosurfactants. *Chem Ecol*. 2015;31(8):707-23.
- 327 19. Hussain A, Hasan A, Javid A, Qazi JI. Exploited application of sulfate-reducing
328 bacteria for concomitant treatment of metallic and non-metallic wastes: a mini review. *3*
329 *Biotech*. 2016;6(2):119.

- 330 20. Giovanella P, Vieira GAL, Ramos Otero IV, Pais Pellizzer E, de Jesus Fontes B, Sette
331 LD. Metal and organic pollutants bioremediation by extremophile microorganisms. *J Hazard*
332 *Mater.* 2020;382:121024.
- 333 21. Taha RA, Mohamedzein YE-A, Al-Rawas AA, Al-Suleimani Y. Solidification of tank
334 bottom sludge. *Geotechnical and Geological Engineering.* 2010;28(1):15.
- 335 22. Hou D, O'Connor D, Igalavithana AD, Alessi DS, Luo J, Tsang DCW, et al. Metal
336 contamination and bioremediation of agricultural soils for food safety and sustainability.
337 *Nature Reviews Earth & Environment.* 2020;1(7):366-81.
- 338 23. Mille G, Guiliano M, Asia L, Malleret L, Jalaluddin N. Sources of hydrocarbons in
339 sediments of the Bay of Fort de France (Martinique). *Chemosphere.* 2006;64(7):1062-73.
- 340 24. Duan J, Liu W, Zhao X, Han Y, O'Reilly S, Zhao D. Study of residual oil in Bay
341 Jimmy sediment 5 years after the Deepwater Horizon oil spill: persistence of sediment
342 retained oil hydrocarbons and effect of dispersants on desorption. *Sci Total Environ.*
343 2018;618:1244-53.
- 344 25. Grote M, van Bernem C, Böhme B, Callies U, Calvez I, Christie B, et al. The
345 potential for dispersant use as a maritime oil spill response measure in German waters. *Mar*
346 *Pollut Bull.* 2018;129(2):623-32.
- 347 26. Souza EC, Vessoni-Penna TC, de Souza Oliveira RP. Biosurfactant-enhanced
348 hydrocarbon bioremediation: An overview. *Int Biodeterior Biodegrad.* 2014;89:88-94.
- 349 27. Mulligan CN. Recent advances in the environmental applications of biosurfactants.
350 *Current Opinion in Colloid & Interface Science.* 2009;14(5):372-8.
- 351 28. Gouma S, Fragoeiro S, Bastos A, Magan N. Bacterial and fungal bioremediation
352 strategies. *Microbial biodegradation and bioremediation: Elsevier; 2014.* p. 301-23.
- 353 29. Chen B, Ye X, Zhang B, Jing L, Lee K. Marine oil spills—Preparedness and
354 countermeasures. *World Seas: An Environmental Evaluation: Elsevier; 2019.* p. 407-26.
- 355 30. Gupta S, Pathak B. Mycoremediation of polycyclic aromatic hydrocarbons.
356 *Abatement of Environmental Pollutants: Elsevier; 2020.* p. 127-49.
- 357 31. Ojuederie OB, Babalola OO. Microbial and Plant-Assisted Bioremediation of Heavy
358 Metal Polluted Environments: A Review. *Int J Env Res Public Health.* 2017;14(12):1504.
- 359 32. Speight JG. Chapter 8 - Biological Transformations. In: Speight JG, editor. *Reaction*
360 *Mechanisms in Environmental Engineering: Butterworth-Heinemann; 2018.* p. 269-306.
- 361 33. Sun W, Zhu B, Yang F, Dai M, Sehar S, Peng C, et al. Optimization of biosurfactant
362 production from *Pseudomonas* sp. CQ2 and its application for remediation of heavy metal
363 contaminated soil. *Chemosphere.* 2021;265:129090.
- 364 34. Marchant R, Banat IM. Microbial biosurfactants: challenges and opportunities for
365 future exploitation. *Trends in biotechnology.* 2012;30(11):558-65.
- 366 35. Banat IM, Franzetti A, Gandolfi I, Bestetti G, Martinotti MG, Fracchia L, et al.
367 Microbial biosurfactants production, applications and future potential. *Applied Microbiology*
368 *and Biotechnology.* 2010;87(2):427-44.
- 369 36. McClements DJ, Gumus CE. Natural emulsifiers — Biosurfactants, phospholipids,
370 biopolymers, and colloidal particles: Molecular and physicochemical basis of functional
371 performance. *Adv Colloid Interface Sci.* 2016;234:3-26.
- 372 37. Hajfarajollah H, Eslami P, Mokhtarani B, Akbari Noghabi K. Biosurfactants from
373 probiotic bacteria: A review. *Biotechnol Appl Biochem.* 2018;65(6):768-83.
- 374 38. Elsoud MMAA. Classification and Production of Microbial Surfactants. *Microbial*
375 *Biosurfactants: Springer; 2021.* p. 65-89.
- 376 39. Sanjana M, Shivalkar Yadav K, Malashree L, Prabha R. Bacterial Biosurfactants-A
377 Boon to Dairy Industry. *Int J Curr Microbiol App Sci.* 2017;6(5):685-9.

- 378 40. Mnif I, Ellouz-Chaabouni S, Ghribi D. Glycolipid Biosurfactants, Main Classes,
379 Functional Properties and Related Potential Applications in Environmental Biotechnology. *J*
380 *Polym Environ*. 2018;26(5):2192-206.
- 381 41. Shoeb E, Akhlaq F, Badar U, Akhter J, Imtiaz S. Classification and industrial
382 applications of biosurfactants. *Academic Research International*. 2013;4(3):243-52.
- 383 42. Herzog M, Tiso T, Blank LM, Winter R. Interaction of rhamnolipids with model
384 biomembranes of varying complexity. *Biochim Biophys Acta*. 2020;1862(11):183431.
- 385 43. Kuyukina MS, Ivshina IB, Baeva TA, Kochina OA, Gein SV, Chereshev VA.
386 Trehalolipid biosurfactants from nonpathogenic *Rhodococcus* actinobacteria with diverse
387 immunomodulatory activities. *New Biotechnology*. 2015;32(6):559-68.
- 388 44. Jimoh AA, Senbadejo TY, Adeleke R, Lin J. Development and Genetic Engineering
389 of Hyper-Producing Microbial Strains for Improved Synthesis of Biosurfactants. *Mol*
390 *Biotechnol*. 2021;63(4):267-88.
- 391 45. Li G, Yi X, Jiang J, Zhang Y, Li Y. Dynamic surface properties and dilational
392 rheology of acidic and lactonic sophorolipids at the air-water interface. *Colloids Surf B*
393 *Biointerfaces*. 2020;195:111248.
- 394 46. Coelho ALS, Feuser PE, Carciofi BAM, de Andrade CJ, de Oliveira D.
395 Mannosylerythritol lipids: antimicrobial and biomedical properties. *Applied microbiology*
396 *and biotechnology*. 2020;104(6):2297-318.
- 397 47. da Silva AF, Banat IM, Giachini AJ, Robl D. Fungal biosurfactants, from nature to
398 biotechnological product: bioprospection, production and potential applications. *Bioprocess*
399 *Biosystems Eng*. 2021;44(10):2003-34.
- 400 48. Tong Y, Zhang J, Wang L, Wang Q, Huang H, Chen X, et al. Hyper-Synergistic
401 Antifungal Activity of Rapamycin and Peptide-Like Compounds against *Candida albicans*
402 Orthogonally via Tor1 Kinase. *ACS Infectious Diseases*. 2021;7(10):2826-35.
- 403 49. Nakamoto H, Yokoyama Y, Suzuki T, Miyamoto Y, Fujishiro T, Morikawa M, et al.
404 A cyclic lipopeptide surfactin is a species-selective Hsp90 inhibitor that suppresses
405 cyanobacterial growth. *The Journal of Biochemistry*. 2021.
- 406 50. Rodríguez-López L, Rincón-Fontán M, Vecino X, Cruz JM, Moldes AB. Extraction,
407 separation and characterization of lipopeptides and phospholipids from corn steep water. *Sep*
408 *Purif Technol*. 2020;248:117076.
- 409 51. Costa SGVAO, Nitschke M, Lépine F, Déziel E, Contiero J. Structure, properties and
410 applications of rhamnolipids produced by *Pseudomonas aeruginosa* L2-1 from cassava
411 wastewater. *Process Biochem*. 2010;45(9):1511-6.
- 412 52. Perfumo A, Banat IM, Canganella F, Marchant R. Rhamnolipid production by a novel
413 thermophilic hydrocarbon-degrading *Pseudomonas aeruginosa* AP02-1. *Applied*
414 *Microbiology and Biotechnology*. 2006;72(1):132-8.
- 415 53. Raza ZA, Khalid ZM, Khan MS, Banat IM, Rehman A, Naeem A, et al. Surface
416 properties and sub-surface aggregate assimilation of rhamnolipid surfactants in different
417 aqueous systems. *Biotechnology letters*. 2010;32(6):811-6.
- 418 54. Franzetti A, Gandolfi I, Bestetti G, Smyth TJP, Banat IM. Production and applications
419 of trehalose lipid biosurfactants. *Eur J Lipid Sci Technol*. 2010;112(6):617-27.
- 420 55. Bages-Estopa S, White DA, Winterburn JB, Webb C, Martin PJ. Production and
421 separation of a trehalolipid biosurfactant. *Biochem Eng J*. 2018;139:85-94.
- 422 56. White DA, Hird LC, Ali ST. Production and characterization of a trehalolipid
423 biosurfactant produced by the novel marine bacterium *Rhodococcus* sp., strain PML026. *J*
424 *Appl Microbiol*. 2013;115(3):744-55.
- 425 57. Kuyukina MS, Ivshina IB. Production of trehalolipid biosurfactants by *Rhodococcus*.
426 *Biology of Rhodococcus*: Springer; 2019. p. 271-98.

- 427 58. Van Bogaert INA, Saerens K, De Muynck C, Develter D, Soetaert W, Vandamme EJ.
428 Microbial production and application of sophorolipids. *Applied Microbiology and*
429 *Biotechnology*. 2007;76(1):23-34.
- 430 59. Elshafie AE, Joshi SJ, Al-Wahaibi YM, Al-Bemani AS, Al-Bahry SN, Al-Maqbali
431 Da, et al. Sophorolipids Production by *Candida bombicola* ATCC 22214 and its Potential
432 Application in Microbial Enhanced Oil Recovery. *Frontiers in Microbiology*. 2015;6(1324).
- 433 60. de Oliveira MR, Camilios-Neto D, Baldo C, Magri A, Celligoi M. Biosynthesis and
434 production of sophorolipids. *Int J Sci Technol Res*. 2014;3:133-43.
- 435 61. Amaral PF, Coelho MAZ, Marrucho IM, Coutinho JA. Biosurfactants from yeasts:
436 characteristics, production and application. *Biosurfactants*. 2010:236-49.
- 437 62. Campos-Takaki GM, Sarubbo LA, Albuquerque CDC. Environmentally friendly
438 biosurfactants produced by yeasts. *Biosurfactants*. 2010:250-60.
- 439 63. Shekhar S, Sundaramanickam A, Balasubramanian T. Biosurfactant Producing
440 Microbes and their Potential Applications: A Review. *Crit Rev Environ Sci Technol*.
441 2015;45(14):1522-54.
- 442 64. Becker F, Stehlik T, Linne U, Bölker M, Freitag J, Sandrock B. Engineering *Ustilago*
443 *maydis* for production of tailor-made mannosylerythritol lipids. *Metabolic Engineering*
444 *Communications*. 2021;12:e00165.
- 445 65. Fu R-M, Tang W, Zhang H, Xue T-T, Chen W-L. Screening of a Mannosylerythritol
446 Lipids Producing Strain and Analysis on Its Products. *Journal of Biobased Materials and*
447 *Bioenergy*. 2021;15(3):408-12.
- 448 66. Jameel A, Haider N. Study the antimicrobial and antiadhesive activity of purified
449 biosurfactant produced from *Lactobacillus plantarum* against pathogenic bacteria. *Iraqi*
450 *Journal of Agricultural Sciences*. 2021;52(5):1194-206.
- 451 67. Joshi-Navare K, Singh PK, Prabhune AA. New yeast isolate *Pichia caribbica*
452 synthesizes xylolipid biosurfactant with enhanced functionality. *Eur J Lipid Sci Technol*.
453 2014;116(8):1070-9.
- 454 68. Oraby A, Werner N, Sungur Z, Zibek S. Factors Affecting the Synthesis of Cellobiose
455 Lipids by *Sporisorium scitamineum*. *Frontiers in Bioengineering and Biotechnology*.
456 2020;8(1280).
- 457 69. Morita T, Ishibashi Y, Fukuoka T, Imura T, Sakai H, Abe M, et al. Production of
458 Glycolipid Biosurfactants, Cellobiose Lipids, by *Cryptococcus humicola* JCM 1461 and
459 Their Interfacial Properties. *Biosci, Biotechnol, Biochem*. 2011;75(8):1597-9.
- 460 70. Khan F, Oloketuyi SF, Kim Y-M. Diversity of Bacteria and Bacterial Products as
461 Antibiofilm and Antiquorum Sensing Drugs Against Pathogenic Bacteria. *Curr Drug Targets*.
462 2019;20(11):1156-79.
- 463 71. Ni'matuzahroh, Sari SK, Trikurniadewi N, Ibrahim SNMM, Khiftiyah AM, Abidin
464 AZ, et al. Bioconversion of agricultural waste hydrolysate from lignocellulolytic mold into
465 biosurfactant by *Achromobacter* sp. BP(1)5. *Biocatalysis and Agricultural Biotechnology*.
466 2020;24:101534.
- 467 72. Lange A, Sun H, Pilger J, Reinscheid UM, Gross H. Predicting the Structure of Cyclic
468 Lipopeptides by Bioinformatics: Structure Revision of Arthrofactin. *ChemBioChem*.
469 2012;13(18):2671-5.
- 470 73. Banat IM, Makkar RS, Cameotra SS. Potential commercial applications of microbial
471 surfactants. *Applied Microbiology and Biotechnology*. 2000;53(5):495-508.
- 472 74. Fei D, Liu F-F, Gang H-Z, Liu J-F, Yang S-Z, Ye R-Q, et al. A new member of the
473 surfactin family produced by *Bacillus subtilis* with low toxicity on erythrocyte. *Process*
474 *Biochem*. 2020;94:164-71.

- 475 75. Kim P-I, Ryu J-W, Kim Y-H, Chi Y-T. Production of biosurfactant lipopeptides iturin
476 A, fengycin, and surfactin A from *Bacillus subtilis* CMB32 for control of *Colletotrichum*
477 *gloeosporioides*. *J Microbiol Biotechnol*. 2010;20(1):138-45.
- 478 76. Drakontis CE, Amin S. Biosurfactants: Formulations, properties, and applications.
479 *Current Opinion in Colloid & Interface Science*. 2020;48:77-90.
- 480 77. Mantil E, Crippin T, Avis TJ. Domain redistribution within ergosterol-containing
481 model membranes in the presence of the antimicrobial compound fengycin. *Biochim Biophys*
482 *Acta*. 2019;1861(4):738-47.
- 483 78. Cortés-Camargo S, Acuña-Avila PE, Arrieta-Báez D, Montañez-Barragán B, Morato
484 AI, Sanz-Martín JL, et al. Biosurfactant Production by *Bacillus tequilensis* ZSB10: Structural
485 Characterization, Physicochemical, and Antifungal Properties. *Journal of Surfactants and*
486 *Detergents*. 2021;24(5):773-82.
- 487 79. González-Jaramillo LM, Aranda FJ, Teruel JA, Villegas-Escobar V, Ortiz A.
488 Antimycotic activity of fengycin C biosurfactant and its interaction with phosphatidylcholine
489 model membranes. *Colloids Surf B Biointerfaces*. 2017;156:114-22.
- 490 80. Gimenez D, Phelan A, Murphy CD, Cobb SL. Fengycin A Analogues with Enhanced
491 Chemical Stability and Antifungal Properties. *Org Lett*. 2021;23(12):4672-6.
- 492 81. Carolin C F, Kumar PS, Ngueagni PT. A review on new aspects of lipopeptide
493 biosurfactant: Types, production, properties and its application in the bioremediation process.
494 *J Hazard Mater*. 2021;407:124827.
- 495 82. Hausmann R, Syldatk C. Types and classification of microbial surfactants.
496 *Biosurfactants: production and utilization—processes, technologies, and economics*.
497 2014;159:1.
- 498 83. Busi S, Rajkumari J. Biosurfactant: A promising approach toward the remediation of
499 xenobiotics, a way to rejuvenate the marine ecosystem. *Marine pollution and microbial*
500 *remediation: Springer*; 2017. p. 87-104.
- 501 84. Vimalnath S, Subramanian S. Studies on the biosorption of Pb (II) ions from aqueous
502 solution using extracellular polymeric substances (EPS) of *Pseudomonas aeruginosa*.
503 *Colloids Surf B Biointerfaces*. 2018;172:60-7.
- 504 85. Qi L, Christopher GF. Role of flagella, type IV Pili, biosurfactants, and extracellular
505 polymeric substance polysaccharides on the formation of pellicles by *Pseudomonas*
506 *aeruginosa*. *Langmuir*. 2019;35(15):5294-304.
- 507 86. Ravindran A, Sajayan A, Priyadharshini GB, Selvin J, Kiran GS. Revealing the
508 efficacy of thermostable biosurfactant in heavy metal bioremediation and surface treatment in
509 vegetables. *Frontiers in Microbiology*. 2020;11:222.
- 510 87. Deng Z, Jiang Y, Chen K, Li J, Zheng C, Gao F, et al. One Biosurfactant-Producing
511 *Bacteria Achromobacter* sp. A-8 and Its Potential Use in Microbial Enhanced Oil Recovery
512 and Bioremediation. *Frontiers in microbiology*. 2020;11:247.
- 513 88. Joe MM, Gomathi R, Benson A, Shalini D, Rengasamy P, Henry AJ, et al.
514 Simultaneous application of biosurfactant and bioaugmentation with rhamnolipid-producing
515 *shewanella* for enhanced bioremediation of oil-polluted soil. *Applied Sciences*.
516 2019;9(18):3773.
- 517 89. Jadeja NB, Moharir P, Kapley A. Genome sequencing and analysis of strains *Bacillus*
518 sp. AKBS9 and *Acinetobacter* sp. AKBS16 for biosurfactant production and bioremediation.
519 *Appl Biochem Biotechnol*. 2019;187(2):518-30.
- 520 90. Huang Y, Zhou H, Zheng G, Li Y, Xie Q, You S, et al. Isolation and characterization
521 of biosurfactant-producing *Serratia marcescens* ZCF25 from oil sludge and application to
522 bioremediation. *Environmental Science and Pollution Research*. 2020;27(22):27762-72.

- 523 91. Patel K, Patel M. Improving bioremediation process of petroleum wastewater using
524 biosurfactants producing *Stenotrophomonas* sp. S1VKR-26 and assessment of phytotoxicity.
525 *Bioresource Technology*. 2020;315:123861.
- 526 92. Durval IJB, Mendonça AHR, Rocha IV, Luna JM, Rufino RD, Converti A, et al.
527 Production, characterization, evaluation and toxicity assessment of a *Bacillus cereus* UCP
528 1615 biosurfactant for marine oil spills bioremediation. *Mar Pollut Bull*. 2020;157:111357.
- 529 93. Hu X, Qiao Y, Chen L-Q, Du J-F, Fu Y-Y, Wu S, et al. Enhancement of
530 solubilization and biodegradation of petroleum by biosurfactant from *Rhodococcus*
531 *erythropolis* HX-2. *Geomicrobiol J*. 2020;37(2):159-69.
- 532 94. Hidayati N, Surtiningsih T. Removal of heavy metals Pb, Zn and Cu from sludge
533 waste of paper industries using biosurfactant. *Journal of Bioremediation and Biodegradation*.
534 2014;5(7).
- 535 95. Vijayanand S, Divyashree M. Bioremediation of heavy metals using biosurfactant
536 producing microorganisms. *Int J Pharm Sci Res*. 2015;6(5):840-7.
- 537 96. Lászlóvá K, Dudášová H, Olejníková P, Horváthová G, Velická Z, Horváthová H, et
538 al. The application of biosurfactants in bioremediation of the aged sediment contaminated
539 with polychlorinated biphenyls. *Water, Air, Soil Pollut*. 2018;229(7):219.
- 540 97. Kreling N, Zapparoli M, Margarites A, Friedrich M, Thomé A, Colla L. Extracellular
541 biosurfactants from yeast and soil–biodiesel interactions during bioremediation. *International*
542 *Journal of Environmental Science and Technology*. 2020;17(1):395-408.
- 543 98. Chrzanowski Ł, Dziadas M, Ławniczak Ł, Cyplik P, Białas W, Szulc A, et al.
544 Biodegradation of rhamnolipids in liquid cultures: effect of biosurfactant dissipation on diesel
545 fuel/B20 blend biodegradation efficiency and bacterial community composition. *Bioresource*
546 *technology*. 2012;111:328-35.
- 547 99. Gidudu B, Mudenda E, Chirwa EM. Biosurfactant Produced by *Serratia* sp. and its
548 Application in Bioremediation Enhancement of Oil Sludge. *Chem Eng*. 2020;79.
- 549 100. Durval IJB, Resende AHM, Figueiredo MA, Luna JM, Rufino RD, Sarubbo LA.
550 Studies on biosurfactants produced using *Bacillus cereus* isolated from seawater with
551 biotechnological potential for marine oil-spill bioremediation. *Journal of Surfactants and*
552 *Detergents*. 2019;22(2):349-63.
- 553 101. Souza KST, Gudiña EJ, Schwan RF, Rodrigues LR, Dias DR, Teixeira JA.
554 Improvement of biosurfactant production by *Wickerhamomyces anomalus* CCMA 0358 and
555 its potential application in bioremediation. *J Hazard Mater*. 2018;346:152-8.
- 556 102. Lee DW, Lee H, Kwon B-O, Khim JS, Yim UH, Kim BS, et al. Biosurfactant-assisted
557 bioremediation of crude oil by indigenous bacteria isolated from Taean beach sediment.
558 *Environ Pollut*. 2018;241:254-64.
- 559 103. Araújo HW, Andrade RF, Montero-Rodríguez D, Rubio-Ribeaux D, da Silva CAA,
560 Campos-Takaki GM. Sustainable biosurfactant produced by *Serratia marcescens* UCP 1549
561 and its suitability for agricultural and marine bioremediation applications. *Microbial cell*
562 *factories*. 2019;18(1):1-13.
- 563 104. Chaprão MJ, Rita De Cássia F, Rufino RD, Luna JM, Santos VA, Sarubbo LA.
564 Production of a biosurfactant from *Bacillus methylotrophicus* UCP1616 for use in the
565 bioremediation of oil-contaminated environments. *Ecotoxicology*. 2018;27(10):1310-22.
- 566 105. Jimoh AA, Lin J. Bioremediation of contaminated diesel and motor oil through the
567 optimization of biosurfactant produced by *Paenibacillus* sp. D9 on waste canola oil.
568 *Bioremediation J*. 2020;24(1):21-40.
- 569 106. Zhou H, Huang X, Liang Y, Li Y, Xie Q, Zhang C, et al. Enhanced bioremediation of
570 hydraulic fracturing flowback and produced water using an indigenous biosurfactant-
571 producing bacteria *Acinetobacter* sp. Y2. *Chem Eng J*. 2020;397:125348.

- 572 107. Nogueira Felix AK, Martins JLL, Lima Almeida JG, Giro MEA, Cavalcante KF,
573 Maciel Melo VM, et al. Purification and characterization of a biosurfactant produced by
574 *Bacillus subtilis* in cashew apple juice and its application in the remediation of oil-
575 contaminated soil. *Colloids Surf B Biointerfaces*. 2019;175:256-63.
- 576 108. Vaishnavi J, Devanesan S, AlSalhi MS, Rajasekar A, Selvi A, Srinivasan P, et al.
577 Biosurfactant mediated bioelectrokinetic remediation of diesel contaminated environment.
578 *Chemosphere*. 2021;264:128377.
- 579 109. Ławniczak Ł, Marecik R, Chrzanowski Ł. Contributions of biosurfactants to natural
580 or induced bioremediation. *Applied microbiology and biotechnology*. 2013;97(6):2327-39.
- 581 110. Jahan R, Bodratti AM, Tsianou M, Alexandridis P. Biosurfactants, natural alternatives
582 to synthetic surfactants: Physicochemical properties and applications. *Adv Colloid Interface*
583 *Sci*. 2020;275:102061.
- 584 111. Singh P, Cameotra SS. Enhancement of metal bioremediation by use of microbial
585 surfactants. *Biochem Biophys Res Commun*. 2004;319(2):291-7.

586