

Potentials for Biosurfactant Enhanced Bioremediation of Hydrocarbon Contaminated Soil and Water – a Review

ABSTRACT

Bioavailability of Hydrophobic Organic Compounds (HOCs) to microorganisms could be a limiting factor during the biodegradation process. Application of surfactants to contaminated soil and water, at concentrations above their Critical Micelle Concentration (CMC) values, can potentially reduce the interfacial tension, increase the solubility and bioavailability of HOCs, and thus, facilitate their biodegradation. Studies with respect to enhanced bioremediation by surfactant addition have greatly focused on chemically synthetic surfactants. This paper reviews the potentials of biosurfactants in remedying contaminated soils and water. Biosurfactants are surface-active substances produced by microorganisms that can degrade or transform the components of petroleum products. They are non-toxic, non-hazardous, biodegradable and environmentally friendly compounds which may be cost effectively produced under ex-situ conditions; in-situ production may be stimulated at the site of contamination and can be recovered and recycled. Their application in bioremediation processes may be more acceptable from a social point of view due to their naturally occurring property. Potential advantages of biosurfactants include their unusual structural diversity that may lead to unique properties, the possibility of cost effective production, and their biodegradability. These properties make biosurfactants a promising choice for applications in enhancing hydrocarbon bioremediation. Biosurfactants have many other applications in various industries such as agriculture, medicine, petroleum, pharmaceutical and cosmetics.

Keywords: Bioavailability, Biosurfactants, Contamination, Hydrophobic Organic Compounds

15 INTRODUCTION

16

17 Soil and water contamination are serious challenges which are caused by inorganic
18 pollutants such as heavy metals and organic pollutants like hydrophobic organic
19 compounds. Heavy metals such as lead (Pb), Cadmium (Cd) Copper (Cu),
20 Chromium (Cr), Zinc (Zn) and Nickel (Ni) are known environmental pollutants and
21 accumulation of these toxic metals in soil and water constitute potential health
22 hazard for man and the ecosystem. HOCs (?????) such as Pentachlorophenol
23 (PCP), Hexachlorobenzene (HCB), Polychlorinated biphenyls (PCBs)
24 and Dichlorophenol (DCP) are known environmental pollutants and their removal
25 from the contaminated sites is a major environmental concern [1].

26 Bioremediation is any process that uses microorganisms or their enzymes to return
27 the environment altered by contaminants to its original condition. It can also be
28 defined as the use of biological processes to degrade or break down contaminants
29 from soil and water. It is a natural process which relies on bacteria, fungi and plants
30 to alter contaminants as these organisms carry out their normal life functions[2].

31 During bioremediation, microbes utilize chemical contaminants in the soil as an
32 energy source and through oxidation-reduction reactions, metabolize the target
33 contaminant into useable energy for microbes. By-products which are called
34 metabolites released back into the environment are usually less toxic than the
35 parent contaminants. For example, petroleum hydrocarbons can be degraded by
36 microorganisms in the presence of oxygen through aerobic respiration. The
37 hydrocarbon loses electrons and is oxidized while oxygen gains electrons and is
38 reduced. The end result of this reaction is the formation of carbon dioxide and water.
39 When oxygen is limited in supply or absent, as in saturated or anaerobic soils or
40 lake sediment, anaerobic respiration occurs [3].

41 Three primary ingredients for bioremediation are: presence of a contaminant,
42 electron acceptor and presence of microorganisms that are capable of degrading
43 the specific contaminant. Generally, a contaminant is more easily degraded if it is a
44 naturally occurring compound in the environment, or chemically similar to a naturally
45 occurring compound, because microorganisms capable of its biodegradation are
46 more likely to have evolved [4].

47 The term bioremediation describes the process of using biological agents to remove
48 toxic waste from environment. Bioremediation is the most effective management
49 tool to manage the polluted environment and recover contaminated soil and is also
50 an attractive and successful cleaning technique for polluted environment [5].

51 Biosurfactants are structurally diverse group of surface-active substances produced
52 by microorganisms. All biosurfactants are amphiphiles, they consist of two parts – a
53 polar hydrophilic moiety and a non polar hydrophobic group. A hydrophilic group
54 consists of mono, oligo or polysaccharides, peptides or proteins and a hydrophobic
55 moiety usually contains saturated, unsaturated and hydroxylated fatty acids or fatty
56 alcohols [6].

57 A characteristic feature of biosurfactants is a hydrophilic-lipophilic balance (HLB)
58 which specifies the portion of hydrophilic and hydrophobic constituents in surface-
59 active substances. Biosurfactants increase the surface area of hydrophobic water-
60 insoluble substances because of their amphiphilic structure and increase the water
61 bioavailability of such substances and change the properties of the bacterial cell
62 surface. Surface activity makes surfactants excellent emulsifiers, foaming and
63 dispersing agents. They are environmentally friendly, biodegradable less toxic and
64 non-hazardous [7].

65 The hydrophilic moiety of a surfactant is defined as the “head”, while the
66 hydrophobic one is referred to as the “tail” of the molecule which generally consists
67 of a hydrocarbon chain of varying length. Surfactants are classified as anionic,
68 cationic, non-ionic and zwitter-ionic, according to the ionic charge of the hydrophilic
69 head of the molecule [8]. Anionic surfactants have higher Critical Micelle
70 Concentrations (CMCs) than nonionic surfactants even when they share the same
71 hydrophobic group. Electrolytes in solution can reduce the CMC by shielding the
72 electrical repulsion among the hydrophilic heads of the molecules; such effect is
73 more pronounced with anionic and cationic surfactants than with nonionic
74 compounds [9]. At concentrations above the CMC, additional quantities of surfactant
75 in solution will promote the formation of more micelles. The formation of micelles
76 leads to a significant increase in the apparent solubility of hydrophobic organic
77 compounds, even above their water solubility limit, as these compounds can
78 partition into the central core of a micelle. The effect of such a process is the

enhancement of mobilization of organic compounds and of their dispersion in solution [10]. This effect is also achieved by the lowering of the interfacial tension between immiscible phases. In fact, this contributes to the creation of additional surfaces, thus improving the contact between different phases [4]. The reduction of interfacial tension is particularly relevant when the pollutant is present in soil as a non-aqueous phase liquid.

The most common hydrophobic parts of chemically synthesized surfactants are paraffins, olefins, alkylbenzenes, alkylphenols and alcohols. The hydrophilic part is usually a sulphate, sulphonate or a carboxylate group in anionic surfactants, a quaternary ammonium group in cationic surfactants and polyoxyethylene, sucrose or a polypeptide in nonionic surfactants [11].

They have many advantages when their chemically synthesized equivalents are compared. They have better foaming properties and higher selectivity. They are active at extreme temperatures, pH and salinity and can be produced from industrial wastes and from by-products. This last feature makes cheap production of biosurfactants possible and allows utilization of waste substrates and reduction of their polluting effect at the same time [12,13,14,15,16].

Biosurfactants produced from microbes such as rhamnolipids, sophorolipid and surfactin and from plants such as saponin have been considered in this paper.

Classification and Properties of Biosurfactants

Biosurfactants are categorized by their chemical composition, molecular weight, physico-chemical properties, mode of action and microbial origin, unlike chemically synthesized surfactants, which are classified according to their dissociation pattern in water. Based on molecular weight they are divided into low-molecular-mass biosurfactants which include glycolipids, phospholipids and lipopeptides (as seen in Table 1) and into high-molecular-mass biosurfactants which are polymeric amphiphiles. Low-molecular-mass biosurfactants are efficient in lowering surface and interfacial tensions, whereas high-molecular-mass biosurfactants are more effective at stabilizing oil-in-water emulsions [17, 18, 19].

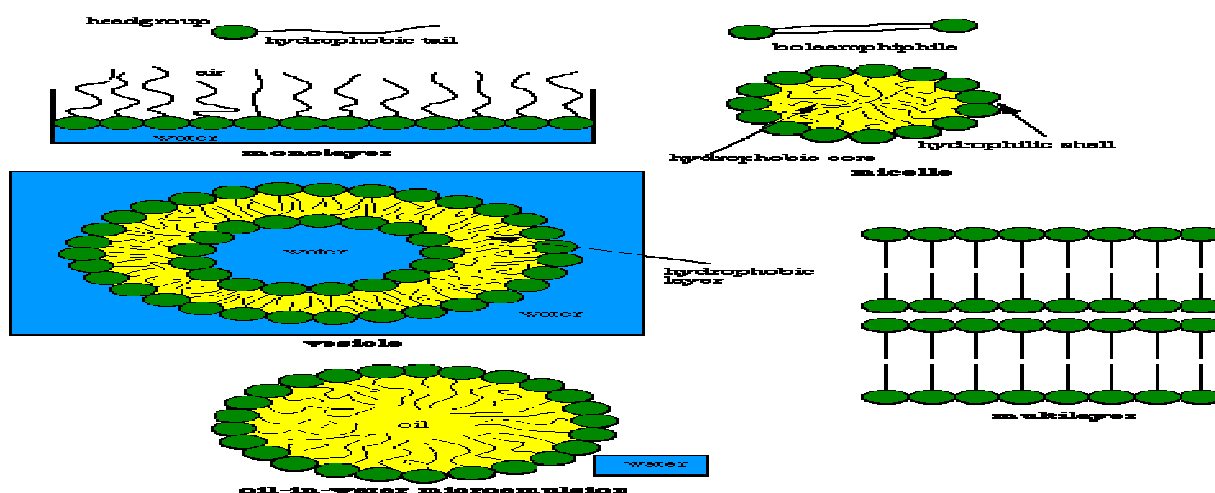
Examples of biosurfactants include: Rhamnolipids produced by *Pseudomonas aeruginosa* [6], Surfactin from *Bacillus subtilis* [20], Mannosylerythritol lipids from

111 *Candida antarticas*) [21], Trehalose lipids from *Rhodococcus erythropolis*[22], Table 1
 112 shows the different types of biosurfactants.

113 Table 1: Classification of Biosurfactants and their use in Remediation of heavy metals and hydrocarbon
 114 contaminated soils

Biosurfactant		Microorganism	Application in Environmental Biotechnology	Refs.
Group	Class			
Glycolipids	Rhamnolipids	<i>Pseudomonas aeruginosa</i> <i>Pseudomonas sp.</i>	Enhancement of the degradation and dispersion of different classes of hydrocarbons; emulsification of hydrocarbons and vegetable oils; Removal of metal from soil.	[23-26]
	Trehalolipids	<i>Mycobacterium tuberculosis</i> , <i>Rhodococcus Erythropolis</i> , <i>Arthrobacter sp.</i> , <i>Nocardia sp.</i> <i>Corynebacterium sp.</i>	Enhancement of the bioavailability of hydrocarbon	27
	Sophololipids	<i>Torulopsis bombicola</i> , <i>Torulopsis petrophilum</i> <i>Torulopsis apicola</i>	Recovery of hydrocarbons from dregs and muds; removal of heavy metals from sediments; enhancements of oil recovery	[24,28,29]
Fatty Acids, Phospholipids and neutral lipids	Corynomycolic acids	<i>Corynebacterium lepus</i>	Enhancement of Bitumen recovery	30
	Spiculisporic acid	<i>Penicillium spiculisporum</i>	Removal of metal ions from aqueous solution; dispersion actions for hydrophilic pigments; preparation of new emulsion-type organogels.	[31-33]
	Phosphatidylethanolamine	<i>Acinetobacter sp.</i> <i>Rhodococcus Erythropolis</i>	Increasing the tolerance of bacteria to heavy metals	34
Lipopeptides	Surfactins	<i>Bacillus subtilis</i>	Enhancement of the biodegradation of hydrocarbons and chlorinated pesticides. Removal of heavy metals from contaminated soil, sediments and water	[35-37]
	Lichenysin	<i>Bacillus licheniformis</i>	Enhancement of oil recovery	38

Biosurfactants accumulate at the interface between two immiscible fluids or between a fluid and a solid. By reducing surface (liquid-air) and interfacial (liquid-liquid) tension; they reduce the repulsive forces between two dissimilar phases and allow these two phases to mix and interact more easily (see Fig. 1) [39].



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(Source: Soberon-Chavez and Maier 2011)

Figure 1. Accumulation of biosurfactants at the interface between liquid and air

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Biosurfactant activities depend on the concentration of the surface-active compounds until the critical micelle concentration is obtained. At concentrations above the CMC, biosurfactant molecules associate to form micelles, bilayers and vesicles (Figure 2). Micelle formation enables biosurfactants to reduce the surface and interfacial tension and increase the solubility and bioavailability of hydrophobic organic compounds [24]. The CMC is commonly used to measure the efficiency of a given surfactant. Efficient biosurfactants have a low CMC, which means that less biosurfactant is required to decrease the surface tension [11].

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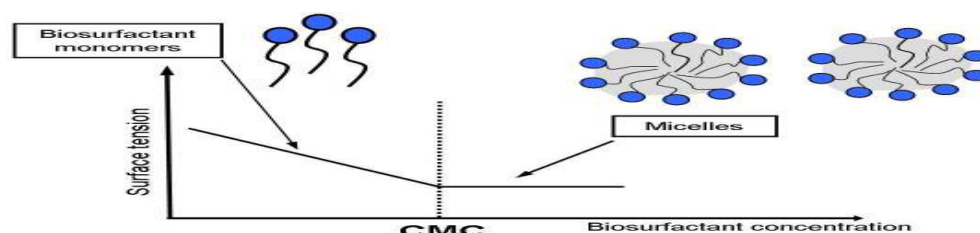


Figure 2. The relationship between biosurfactant concentration, surface tension and formation of micelles

143 **Role of Biosurfactants in Biodegradation Processes**

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145 Biosurfactants can enhance hydrocarbon bioremediation by two mechanisms. The
146 first is the increase of substrate bioavailability for microorganisms, while the other
147 involves interaction with the cell surface which increases the hydrophobicity of the
148 surface allowing hydrophobic substrates to associate more easily with bacterial cells
149 [40]. By reducing surface and interfacial tensions, biosurfactants increase the
150 surface areas of insoluble compounds leading to increased mobility and
151 bioavailability of hydrocarbons. Consequently, biosurfactants enhance
152 biodegradation and removal of hydrocarbons from contaminated environments.
153 Addition of biosurfactants is expected to enhance hydrocarbon biodegradation by
154 mobilization, solubilization or emulsification [41,42, 43,14].

155

156 The mobilization mechanism occurs at concentrations below the biosurfactant CMC.
157 At such concentrations, biosurfactants reduce the surface and interfacial tension
158 between air/water and soil/water systems. Due to the reduction of the interfacial
159 force, contact of biosurfactants with soil/oil system increases the contact angle and
160 reduces the capillary force holding oil and soil together. This causes solubilization to
161 take place above the biosurfactant CMC. At these concentrations biosurfactant
162 molecules associate to form micelles, which dramatically increase the solubility of
163 oil. The hydrophobic ends of biosurfactant molecules connect together inside the
164 micelle while the hydrophilic ends are exposed to the aqueous phase on the
165 exterior. Consequently, the interior of a micelle creates an environment compatible
166 for hydrophobic organic molecules. The process of incorporation of these molecules
167 into a micelle is known as solubilization [44].

168 Interest in microbial surfactants has been progressively escalating in recent years
169 due to their diversity, environmentally friendly nature, possibility of large-scale
170 production, selectivity, performance under intense circumstances and their
171 impending applications in environmental fortification [7].

172

173 **Biosurfactant Enhanced Remediation of Hydrophobic Substances in Soil**

174 Wide application and improper disposal of oil products and other hazardous wastes,
175 as well as accidents related to them result in long-lasting contamination of soil and

176 subsurface environment. Contamination inevitably will affect ecosystems and
177 human health [45]. Blend of glycolipid-based anionic biosurfactant was used to
178 investigate this. The biosurfactant was purchased as 5 wt % solution with pH value
179 of 10, CMC was 0.1 % (surface tension-27 mN/m) and the HLB was 10.

180 Before practical application to remove oil or other hydrophobic substances from soil,
181 the behaviour of the biosurfactant across different systems was examined. Process
182 variables, temperature of environment, contact time with dilution of biosurfactant,
183 and concentration of biosurfactant in washing solution were modeled by applying full
184 factorial design.

185 Many physical properties used to characterize surfactants depend on the CMC,
186 emulsion, oil solubilization, foaming and detergency, interfacial and surface
187 tensions. These properties may be used to assess the suitability of surfactant for
188 environmental bioremediation, such as soil washing. They used the Photo
189 colorimetric method in their research to determine the cleaning efficiency instead of
190 the generally gravimetric assessment. The experimental tests showed high reliability
191 for the assessment of degreasing and therefore are especially suited for exploration
192 and optimization of different surfactants and their mixes [45].

193 Both organic and inorganic contaminants can be removed through desorption or
194 biodegradation processes. Biosurfactants enhance the desorption of heavy metals
195 or HOCs from soils in two ways: directly by favouring metals or HOCs solubility from
196 soils and indirectly by increasing the metals or HOCs availability to the plants [1].

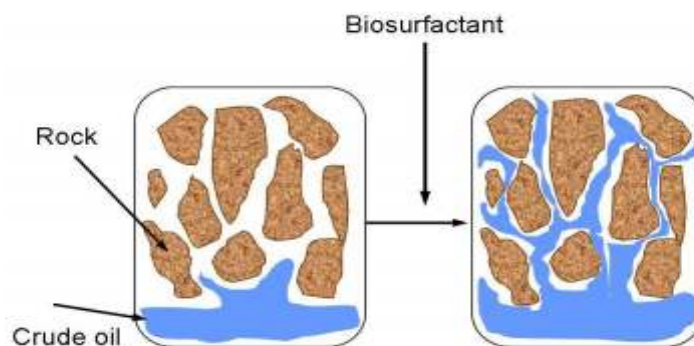
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198 **Other uses of Biosurfactants**

199 Biosurfactants are used in various industries such as food, pharmaceutical and
200 cosmetic, as they are biodegradable and less toxic than the synthetic surfactants
201 currently used [46]. The most important surface-active properties evaluated in
202 screening microorganisms for biosurfactants with potential industrial applications are
203 surface tension reduction, emulsion forming and stabilizing capacity. The criterion
204 used for selection of biosurfactant producers is the ability to reduce the surface
205 tension below 40 mN m⁻¹ [47]. Sophorose lipids produced by certain strains of yeast
206 have been formulated for anti-dandruff solutions, hair gels, deodorant sticks, after-
207 shave lotions, and hair and body shampoos.

208 **Microbial Enhanced Oil Recovery (MEOR)**

209 Biosurfactants can also be involved in microbial enhanced oil recovery. This
210 method is used to recover oil remaining in reservoirs after primary and secondary
211 recovery procedures [48, 49]. It is an important tertiary recovery process where
212 microorganisms or their metabolites, including biosurfactants, biopolymers,
213 biomass, acids, solvents, gases and also enzymes, are used to increase recovery of
214 oil from depleted reservoirs. Application of biosurfactants in enhanced oil recovery is
215 one of the most promising advanced methods to recover a significant proportion of
216 residual oil. The remaining oil is often located in regions of the reservoir that are
217 difficult to access and the oil is trapped in the pores by capillary pressure.
218 Biosurfactants reduce interfacial tension between oil/water and oil/rock. This
219 reduces capillary forces preventing oil from moving through the rock pores (Fig. 3).
220 Surfactants can also bind tightly to the oil-water interface and form emulsion. This
221 stabilizes the desorbed oil in water and allows removal of oil along with the injection
222 water [50].



223
224 Source: Pacwa-Plociniczak, *et al*, 2011

225 Fig. 3: Mechanism of enhanced oil recovery by biosurfactants.

226
227 Tertiary oil recovery experiments showed that biosurfactant solutions with
228 concentrations ranging from 10 to 60 mg/l in the presence of 0.1 mM 2,3-butanediol
229 and 1 g/l of partially hydrolyzed polyacrylamide (PHPA) recovered 10-40% of the
230 residual oil present in Berea sandstone cores. When PHPA was used alone, about
231 10% of the residual oil was recovered. Thus, about 10% of the residual oil recovered
232 in these experiments was due to the increase in viscosity of the displacing fluid. The
233 remainder of the recovered oil was due to the effect of the JF-2 biosurfactant on
234 interfacial tension between oil and the displacing aqueous phase. Little or no oil was
235 recovered at biosurfactant concentrations below the CMC (about 10 mg/l). Below

this concentration, the IFT(?????) values were high. At biosurfactant concentrations between 10 and 40 mg/l, the IFT was 1 mN/m. When the CMC is greater than 40 mg/l, IFT decreased to around 0.1 mN/m. At biosurfactant concentrations above the CMC, residual oil recovery is a linear function of biosurfactant concentration[50].

Biosurfactants and Metals Remediation

Contamination of soil environments with heavy metals is very hazardous for human and other living organisms in the ecosystem. As a result of their extremely toxic nature, presence of even low concentrations of heavy metals in the soils has been found to have serious consequences. Currently, there are many techniques used to clean up soils contaminated with heavy metals. Remediation of these soils includes non-biological methods such as excavation and disposal of contaminated soil to landfill sites or biological techniques[51, 52].

A promising approach seems to be the application of inoculants of biosurfactant producing bacteria in phytoremediation of hydrocarbon polluted soil to improve the efficiency of this technology. Application of the biosurfactants in phytoremediation on a large scale requires studies to identify their potential toxic effect on plants. Although the biosurfactants are thought to be ecofriendly, some experiments indicated that under certain circumstances they can be toxic to the environment[38]. Nevertheless, careful and controlled use of these interesting surface active molecules will surely help in the enhanced cleanup of the toxic environmental pollutants and provide us with a clean environment [2].

Application of Biosurfactant Technology on Contaminated Soils

Remediation of heavy metals pollution

Hong *et al.* [54] examined the removal of cadmium and zinc, by saponin, (a plant-derived biosurfactant) from three types of soils - Andosol Cambisol, and Regosol soils. Rates of removal of 90–100% for cadmium and 85–98% for zinc were obtained. Saponin concentrations of 3% were optimal for metal removal within 6 hours and maximal removal was obtained from Regosol soil.

Rhamnolipid produced by *Pseudomonas* bacteria which has a strong affinity for metals such as Cd, Zn and Pb has been used in soil washing in recent years. Heavy metal removal from a sandy soil contaminated with 1710 mg/kg of Cd and 2010 mg/kg of Ni was studied by Mulligan and Wang [55] and maximum removal was obtained by foam produced by 0.5% rhamnolipid solution, after 20 pore volumes. Removal efficiency for the biosurfactant foam was 73.2% of Cd and 68.1% of Ni while removal efficiency for the biosurfactant liquid solution was 61.7% Cd and 51.0% Ni.

Rhamnolipid biosurfactant produced by *Pseudomonas aeruginosa* was also evaluated by Juwarkar *et al.*, [56] to know the potential of removing Cd and Pb from contaminated soil. Their results showed that di-rhamnolipid removed not only the leachable or available fraction of Cd and Pb but also the bound metals as compared to tap water which removed the mobile fraction only.

Mulligan *et al.*, [57] evaluated the possibility of using surfactin, rhamnolipid, and sophorolipid for the removal of Cu and Zn, from sediments. A single washing with 0.5% rhamnolipid removed 65% of the copper and 18% of the zinc, 4% sophorolipid removed 25% of the copper and 60% of the zinc while surfactin was the least effective, removing 15% of the copper and 6% of the zinc.

Remediation of Hydrophobic Organic Compounds

Pentachlorophenol (PCP) is a toxic, suspected carcinogenic compound which can be used to preserve wood. A rhamnolipid biosurfactant was used to investigate the removal efficiency in soils contaminated with PCP; 1% of the rhamnolipid removed 60% and 61% of PCP from fine sand soil and sandy-silt soil respectively, contaminated with 1000 mg/kg PCP. Of this, 36% and 44% of the PCP was removed by volatilization by the biosurfactant [58].

A plant-based surfactant extracted from fruit pericarps of *Sapindus mukorossi* was proposed for remediation of hexachlorobenzene (HCB) contaminated soil. HCB concentration in the natural surfactant solution approached up to 90% of the HCB solubility in the respective solutions in batch desorption studies for soils contaminated to high levels, and the HCB recoveries were up to 90% of the total HCB for soils contaminated to lower levels [59].

Biosurfactants exhibited much higher Total Petroleum Hydrocarbon (TPH) removal efficiency than the tested synthetic ones as observed by the experimental results from Lai *et al.*, [60]. By using 0.2 mass% of rhamnolipids, surfactin, Tween 80, and Triton X-100, the TPH removal from the soil contaminated with ca. 3,000 mg TPH/kg dry soil was 23%, 14%, 6%, and 4%, respectively, while removal efficiency increased to 63%, 62%, 40%, and 35%, respectively, for the soil contaminated with ca. 9000 mg TPH/kg dry soil.

Rahman *et al.* [14] demonstrated that addition of rhamnolipid produced by *Pseudomonas sp.* along with poultry waste and coir pith enhanced ex situ bioremediation of a gasoline-contaminated soil. Research with another strain, *Pseudomonas marginalis*, also indicated that the produced biosurfactants

320 solubilized (PAHs) such as phenanthrene and enhanced biodegradation [61]. The
321 rhamnolipids sorbed onto the solids, thus increasing the amount of solid phase
322 PAHs.

323

324 The study of sophorolipids effects on phenanthrene biodegradation showed that the
325 concentration of phenanthrene with initial concentration of 80 mg/L within 36 hour
326 decreased to 0.5 mg/L in the presence of 500 mg/L of the surfactant compared to
327 2.3 mg/L without surfactant in a 10% soil suspension [62]. The maximal degradation
328 by *Sphingomonas yanoikuyae* was 1.3 mg/L/h with the sophorolipid instead of 0.8
329 mg/L/h. The sophorolipids seem to enhance the phenanthrene concentration as
330 shown by fluorescence measurements instead of increasing biomass concentration.
331 In addition, toxicity of the sophorolipid was low for concentrations up to 1 g/L. The
332 CMC of the sophorolipid in water was 4 mg/L but this increased to 10 mg/L in the
333 presence of 10% soil suspensions indicating adsorption of the surfactant onto the
334 soil.

335

336 Biosurfactants have been shown to promote biodegradation of hydrocarbons and a
337 pilot plant and large scale bioremediations of soil contaminated with polycyclic
338 aromatic hydrocarbons (PAH) and heavy oil were performed. In the presence of
339 selected biosurfactants, a preferential and significant removal of PAHs was
340 observed after only 22 days of bioremediation. These results show a significant
341 reduction of the time required to bioremediate contaminated sites bearing in mind
342 that bioremediation is generally a slow process[13].

343 The compound used for the experiment, 2,4-dichlorophenol (2,4-DCP), was
344 considerably more degraded when sophorose lipids were added to the soil slurry
345 (Fig. 4). Decrease of 2,4 –DCP in the suspensions was found to be generally a slow
346 process for the first 8 days. However, a sharp drop in the suspension was observed
347 afterwards (Fig. 4a, b). In the presence of sophorose lipids, this drop was
348 significantly deeper as compared to the sample without sophorose lipids.

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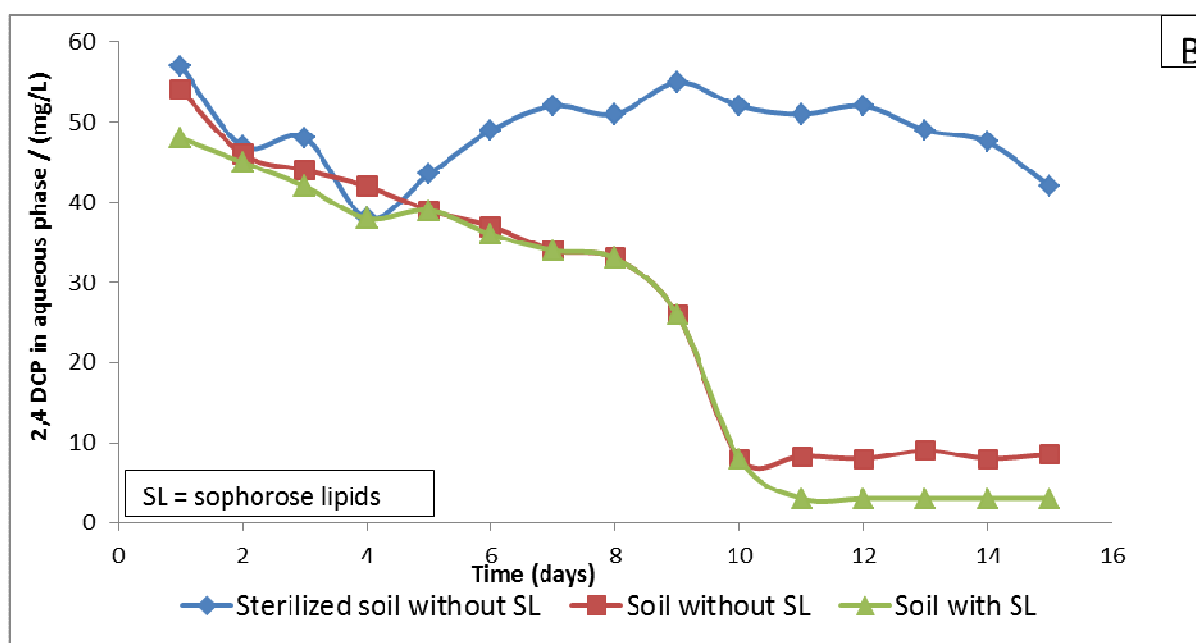
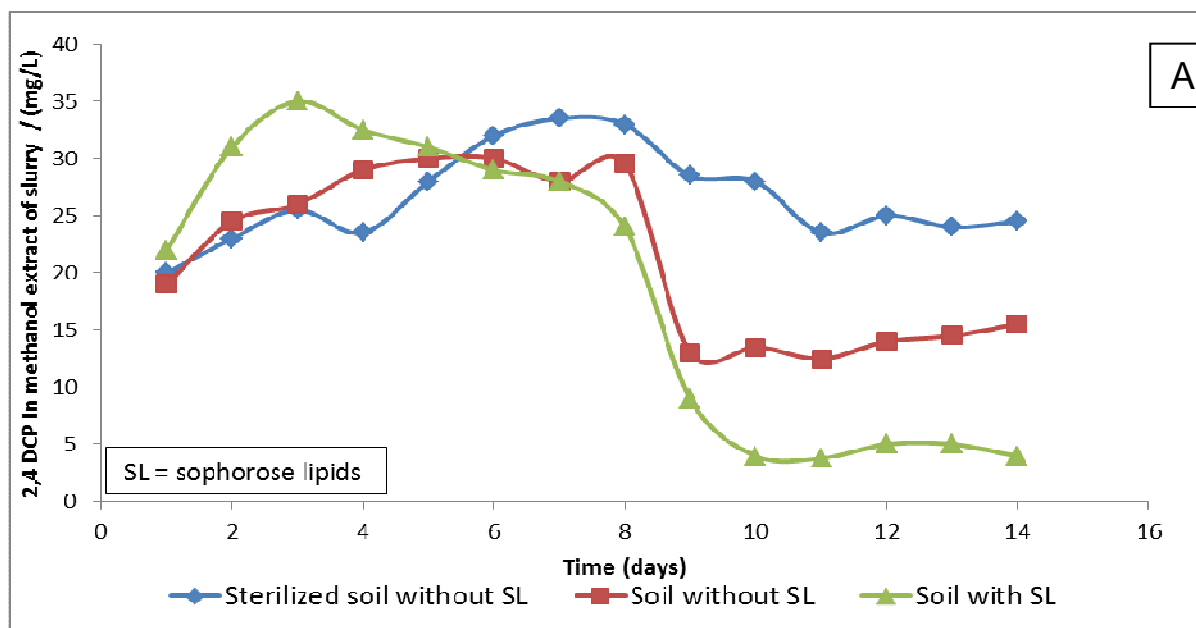


Fig 4: The effect of Sophorose lipids on 2,4 Dichlorophenol in soil suspension: (A) in methanol extract of slurry (B) in Aqueous Phase (soil 40g; water 60 ml; 2,4 DCP 6g; sophorose 38mg) [13].

Advantages of bioremediation

1. Bioremediation is a natural process and is generally perceived as an acceptable waste treatment process for contaminated material such as soil. Microbes able to degrade the contaminant increase in numbers when the

360 contaminant is present; when the contaminant is degraded, the
361 biodegradative population declines. The residues for the treatment are
362 usually harmless products such as carbon dioxide, water and cell biomass.
363 2. Bioremediation is useful for the complete destruction of a wide variety of
364 contaminants. Many compounds that are hazardous can be transformed to
365 harmless products.
366 3. Instead of transferring contaminants from one environment to another for
367 example land to water or air, the complete destruction of the target pollutants
368 is possible.
369 4. Bioremediation is less expensive than other technologies that are used for
370 other clean-up of hazardous wastes.

371 **Disadvantages of bioremediation**

372 1. Bioremediation is limited to those compounds that are biodegradable. Not all
373 compounds are susceptible to rapid and complete degradation.
374 2. There are some concerns that the products of biodegradation may be more
375 toxic than the parent compound.
376 3. Biological processes are often highly specific. Important site factors required
377 for success include the presence of metabolically capable microbial
378 populations, suitable environmentally capable microbial populations, suitable
379 environmental growth conditions and appropriate levels of nutrients and
380 contaminants.
381 4. Bioremediation often takes longer than other treatment options, such as exc-
382 avation and removal of soil or incineration.
383 5. Prolonged exposure of skin to biosurfactants can cause chafing because
384 surfactants (like soaps) disrupt the lipid coating that protects the skin and
385 other cells.

386 **CONCLUSION**

387 Biosurfactants have shown their potential for remediation of contaminated soils by increasing
388 biodegradation rate and reducing contaminant minimum concentration.
389 Soil and water that are contaminated with organic and inorganic pollutants can be effectively
390 treated with biosurfactants.
391 Bioremediation is a biological process that degrades or breaks down contaminants from soil
392 and water naturally with the help of bacteria, fungi and plants.
393 The value of CMC determines the ability of biosurfactants to reduce the surface tension and
394 interfacial tension and increase the solubility and bioavailability of hydrophobic organic
395 compounds.
396 Bioremediation is often a longer treatment option and prolonged exposure of biosurfactants
397 to skin can be very harmful.
398 Biosurfactants have several applications in various industries such as agriculture, petroleum
399 sector – microbial enhanced oil recovery, medicine, pharmaceutical and cosmetic industries.

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582 ABBREVIATIONS

- 583
584
585 **CMC** Critical Micelle Concentration
586 **DCP** Dichlorophenol
587 **HCB** Hexachlorobenzene
588 **HLB** Hydrophilic-Lipophilic Balance
589 **HOC** Hydrophobic Organic Compounds
590 **PAH** Polycyclic aromatic Hydrocarbon
591 **PCP** Pentachlorophenol
592 **PHPA** Hydrolyzed Polyacrylamide
593 **TPH** Total Petroleum Hydrocarbon