



Potentials for Biosurfactant Enhanced Bioremediation of Hydrocarbon Contaminated Soil and Water—A Review

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Authors' contributions

This work was carried out in collaboration between both authors. Author OSE designed the study, wrote the protocol and wrote the first draft of the manuscript. Author AJU managed the literature searches, analyses of the study and final manuscript. Both authors read and approved the final manuscript.

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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

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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.

ABBREVIATIONS

CMC-Critical Micelle Concentration; DCP-Dichlorophenol; HCB-Hexachlorobenzene; HLB-Hydrophilic-Lipophilic Balance; HOC-Hydrophobic Organic Compounds; IFT-Interfacial Tension; MEOR-Microbial Enhanced Oil Recovery; PAH-Polycyclic aromatic Hydrocarbon; PCP-Pentachlorophenol; PHPA-Partially Hydrolyzed Polyacrylamide; TPH-Total Petroleum Hydrocarbon.

1. INTRODUCTION

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

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

Chemical contaminants in the soil are used by microbes as energy source to mobilize the target contaminants into usable energy during bioremediation. The metabolites discharged into

the environment are less toxic than the original contaminants. Petroleum hydrocarbons can be degraded by two ways: Aerobic respiration (sufficient oxygen) and anaerobic respiration (insufficient or lack of oxygen). The end product of this reaction is usually carbon dioxide and water [3].

Three main conditions required for bioremediation are: Availability of contaminant, electron acceptor and microorganisms with the ability to degrade contaminants. Degradation of contaminants are made easy if the microorganisms to be used, occur naturally in the environment [4].

The term bioremediation describes the process of using biological agents to remove toxic waste from environment. Bioremediation is the most effective management tool to manage polluted environments and restore contaminated soil to its original state and is also an attractive and successful cleaning technique for polluted environments [5].

Microorganisms produce different groups of surface-active substances called Biosurfactants. These biosurfactants are amphiphiles which consist of two parts: A polar hydrophilic group and a non-polar hydrophobic group. Examples of hydrophilic group are the mono, polysaccharides, peptides or proteins and the hydrophobic group are the saturated, unsaturated and hydroxylated fatty acids or fatty alcohols [6].

A notable feature of biosurfactants is a Hydrophilic-Lipophilic Balance (HLB) which specifies the part of the compound that is hydrophilic and the one that is hydrophobic. The amphiphilic structure of biosurfactants, enables them to increase the surface area of hydrophobic water-insoluble substances, increase the water bioavailability and alter the properties of the bacterial cell surface. These characteristics make biosurfactants to be used as emulsifiers, foaming and dispersing agents. They are ecofriendly, easily biodegradable, harmless and non-hazardous [7].

The hydrophilic part of the surfactant is called the "head", while the hydrophobic part is the "tail" of the molecule, which generally consists of hydrocarbon chain of varying length. Surfactants are classified as anionic, cationic, non-ionic and zwitter-ionic, according to the ionic charge of the hydrophilic head of the molecule [8]. Anionic surfactants have higher Critical Micelle Concentrations (CMCs) than nonionic surfactants. The CMC can be reduced by shielding the electrical repulsion among the hydrophilic heads of the molecules especially in anionic and cationic surfactants [9]. Additional quantities of surfactant in solution will result in the formation of more micelles above the CMC, which leads to significant increase in the apparent solubility of hydrophobic organic compounds. Such process will cause mobilization improvement in organic compounds and their spread in solution [10]. This process also causes reduction of interfacial tension between immiscible phases [4]. When a pollutant occurs in the soil as a non-aqueous phase liquid, it makes the interfacial tension reduction imperative.

Common hydrophobic parts of synthesized surfactants are paraffins, olefins, alkylbenzenes, alkylphenols and alcohols and common hydrophilic parts are sulphates, sulphonates or carboxylate groups in anionic surfactants. The hydrophilic part in cationic surfactants is the quaternary ammonium group and in the nonionic surfactants the polyoxyethylene, sucrose or polypeptide [11].

They have many advantages when their chemically synthesized equivalents are compared. They possess better foaming characteristics, higher selectivity and they work well in extreme temperatures, pH and salinity and can be produced from industrial wastes. Cheap production of biosurfactants is possible because of this last feature as well as utilization

of waste substrates and reduction of their polluting effects [12-16].

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

1.1 Classification and Properties of Biosurfactants

Biosurfactants are classified based on their chemical composition, molecular weight and physico-chemical properties unlike the chemically synthesized surfactants, which are classified based on their pattern of dissociation in water. In terms of molecular weight there are low-molecular-mass biosurfactants which include glycolipids, phospholipids and lipopeptides; (see Table 1) and high-molecular-mass biosurfactants which are polymeric amphiphiles. Low-molecular-mass biosurfactants are good in surface and interfacial tensions reduction while, high-molecular-mass biosurfactants are good in oil-in-water emulsions stabilization [17-19].

The following are examples of biosurfactants: *Pseudomonas aeruginosa* microorganisms which produce Rhamnolipids [6], *Bacillus subtilis* produce Surfactin [20], *Candida antarticas* produce Mannosylerythritol lipids [21], *Rhodococcus erythropolis* produce Trehalose lipids [22]. Table 1 shows the different types of low-molecular-mass biosurfactants.

Biosurfactants gather over a period of time at the interface between two phases; either two immiscible fluids or a fluid and a solid [23]. The reduction of the repulsive forces between two dissimilar phases allows them to mix and interact more easily (see Fig. 1) [24]. This ultimately reduces surface (liquid/air) and interfacial (liquid/liquid) tensions.

The activities of biosurfactant depend on the surface-active compounds concentration until the CMC is reached. Above the CMC, micelles, bilayers and vesicles are formed by biosurfactant compounds (Fig. 2). The formation of micelles allows biosurfactants to reduce the surface and interfacial tension and increase the solubility and bioavailability of HOCs [25]. The CMC is a means of measuring a given biosurfactant efficiency. When the value of CMC is low, it means that less biosurfactant is needed for surface tension reduction [11].

Table 1. Biosurfactants classifications and their application in biotechnology

Group	Biosurfactant Class	Microorganism	Application in environmental biotechnology	Refs.
Glycolipids	Rhamnolipids	<i>Pseudomonas aeruginosa</i> <i>Pseudomonas</i> sp.	Degradation improvement and hydrocarbon dispersion in solution; hydrocarbon and vegetable oils emulsification; metal removal from contaminated soil.	[25-28]
	Trehalolipids	<i>Mycobacterium tuberculosis</i> , <i>Rhodococcus erythropolis</i> , <i>Arthrobacter</i> sp. <i>Nocardia</i> sp. <i>Corynebacterium</i> sp.	Improvement of the hydrocarbon bioavailability	[29]
	Sophololipids	<i>Torulopsis bombicola</i> , <i>Torulopsis petrophilum</i> <i>Torulopsis apicola</i>	Hydrocarbon recovery from dregs and muds; heavy metal removal from sediments; oil recovery improvement	[25,30,31]
Fatty Acids, Phospholipids and neutral lipids	Corynomycolic acids	<i>Corynebacterium lepus</i>	Improvement of Bitumen recovery	[32]
	Spiculisporic acid	<i>Penicillium spiculisporum</i>	Metal recovery from aqueous solution; hydrophilic pigments dispersion in solution; enhances formation of new emulsion-type organogels.	[33-35]
	Phosphatidyethanolamine	<i>Acinetobacter</i> sp. <i>Rhodococcus erythropolis</i>	Allows the bacteria in the heavy metals	[36]
Lipopeptides	Surfactins	<i>Bacillus subtilis</i>	Improves the biodegradation of hydrocarbons and chlorinated pesticides. Removal of heavy metals from contaminated soil, sediments and water	[37-39]
	Lychenysin	<i>Bacillus licheniformis</i>	Enhancement of oil recovery	[40]

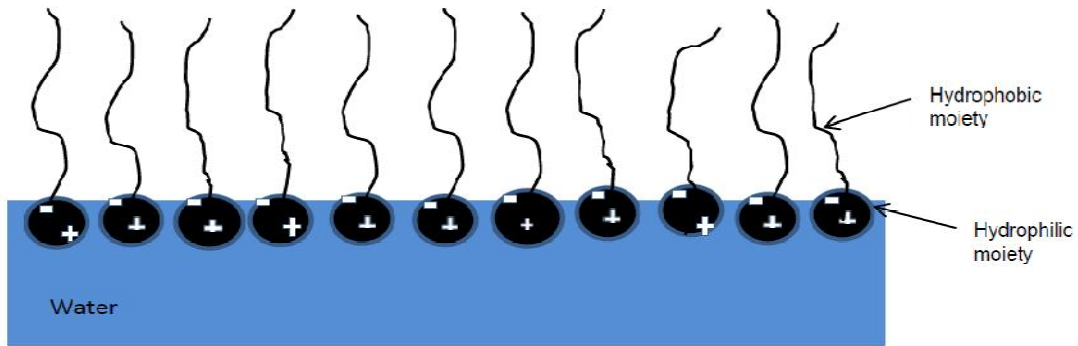


Fig. 1. Biosurfactant accumulation at the liquid/air interface [24]

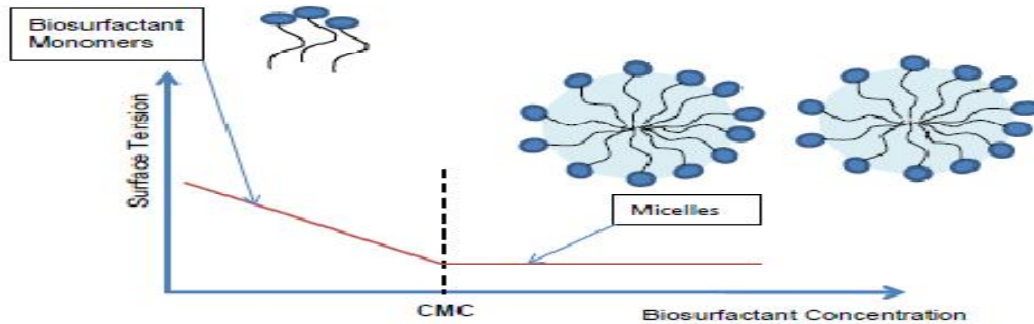


Fig. 2. Relationship between biosurfactant concentration, surface tension and formation of micelles [25]

1.2 Role of Biosurfactants in Biodegradation Processes

Biosurfactants improves hydrocarbon bioremediation by two methods:

- (i) Substrate bioavailability increase for microorganisms and
- (ii) Cell surface interaction which increases the hydrophobicity of surface and allows the hydrophobic substrates to associate more easily with bacterial cells [41].

Biosurfactant increase the surface areas of insoluble compounds by surface tension reduction causing increase in mobility and bioavailability of hydrocarbons. Consequently, biosurfactants improves biodegradation and hydrocarbon removal from contaminated environments. Three processes are used by biosurfactants to improve biodegradation of hydrocarbon: Mobilization, solubilization or emulsification [42-44,14].

Mobilization occurs below the CMC, where the surface and interfacial tension is reduced between air/water and soil/water systems. When this happens the biosurfactant increase the contact angle in the soil/oil system and reduces the capillary forces holding the oil and soil together. Solubilization occurs above the CMC where the micelles are formed and the oil solubility is increased. The hydrophobic ends of biosurfactant molecules join together inside the micelle while the hydrophilic ends are exposed on the exterior to the aqueous phase. Consequently, a compatible environment for the hydrophobic organic molecule is created by the interior of a micelle [45].

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

1.3 Biosurfactant Enhanced Remediation of Hydrophobic Substances in Soil

Long-lasting contamination of soil and subsurface environment is caused by indiscriminate disposal of oil products and other hazardous wastes, which adversely affect the ecosystems and man [46]. Blend of glycolipid-based anionic biosurfactant was used to investigate this. The biosurfactant was purchased as 5 wt% solution with pH value of 10, CMC was 0.1% (surface tension-27 mN/m) and the HLB was 10.

Before practical application to remove contaminants from soil, the biosurfactant behaviour in different systems was examined. Three process variables were modeled with full factorial to study the practical application of biosurfactants: Temperature of the environment, contact time with dilution of biosurfactant and biosurfactant concentration in washing solution.

Biosurfactants can be characterized by some physical properties depending on the CMC, emulsion, oil solubilization, foaming and detergency, interfacial and surface tensions. These properties may be used to know if the biosurfactants are suitable for environmental bioremediation. Results from experiments have shown that they are useful for degreasing and can therefore be suitable for exploration and optimization of various kinds of surfactants [46].

Both organic and inorganic contaminants can be removed through desorption or biodegradation processes. Biosurfactants can be used to increase the desorption of heavy metals and HOCs from soils in two ways:

- i. Enhancing the solubility of the metals and the HOCs in soils
- ii. Increasing the availability of the metals and HOCs to the plants [1].

1.4 Other uses of Biosurfactants

Biosurfactants are used in various industries such as food, pharmaceutical and cosmetic, as they are biodegradable and less toxic than the synthetic surfactants currently used [47]. The most important surface-active properties evaluated in screening microorganisms for biosurfactants with potential industrial applications are surface tension reduction, emulsion forming and stabilizing capacity. The

criterion used for selection of biosurfactant producers is the ability to reduce the surface tension below 40 mN m⁻¹ [48]. Sophorose lipids produced by certain strains of yeast have been formulated for anti-dandruff solutions, hair gels, deodorant sticks, after-shave lotions and hair and body shampoos.

1.5 Microbial Enhanced Oil Recovery (MEOR)

Microbial enhanced oil recovery (MEOR) is the use of biosurfactant to improve oil recovery from depleted reservoirs. Enhanced oil recovery is also called tertiary recovery process which is any other process used to recover the remaining oil in the reservoir after the primary and secondary recovery processes [49,50]. The primary recovery process involves the natural energy of the reservoir while the secondary recovery process is usually water or gas flooding operations. In MEOR, microorganisms or other metabolites which include biosurfactants, biopolymers, biomass, acids, solvents, gases and enzymes, are applied to increase oil recovery from depleted reservoirs. The use of biosurfactants in enhanced oil recovery is one of the modern techniques for recovery of substantial amount of residual oil. The residual oil is usually trapped in the pores of rocks by capillary pressure and application of biosurfactants, reduces the interfacial tensions between the oil/water and oil/rock interface. Consequently, the capillary forces that prevent oil from moving through the rock are reduced considerably and allow the oil to flow upwards. This process also causes wettability alteration in the rock. See Fig. 3. Surfactants also form emulsion when they bind tightly to the oil-water interface. When emulsion occurs, the desorbed oil in water is stabilized and oil is recovered along with the injection water [51,52].

Berea sandstone cores were used in MEOR experiments and it was found that biosurfactant solutions with 10 to 60 mg/l concentration range in the presence of 0.1 mM 2,3-butanediol and 1 g/l of partially hydrolyzed polyacrylamide (PHPA) could recover 10-40% of the residual oil. When PHPA was used, the residual oil recovered was about 10%. It can be inferred that the 10% residual oil recovered was because of the viscosity increase of the displacing fluid while the rest of the recovered oil was due to the effect of JF-2 biosurfactant interfacial tension reduction. Below CMC concentration, (about 10 mg/l) little or no oil was recovered. Below CMC

concentration the Interfacial Tension (IFT) values were high. Between 10 to 40 mg/l, of biosurfactant concentration, the IFT was 1 mN/m while above 40 mg/l, the IFT decreased to around 0.1mN/m. Thus, at biosurfactant concentrations above the CMC, residual oil recovery is a linear function of biosurfactant concentration [51].

1.6 Biosurfactants and Metals Remediation

Man and other living organisms in the ecosystem have been affected by soils contaminated with heavy metals. The presence of even low concentrations of heavy metals in the soil, have proven to have serious consequences because of its toxic nature. Currently, many methods are adopted to remove heavy metals from contaminated soils. These methods include non-biological techniques like excavation and disposal to landfill sites and biological techniques [53,54]. In biological techniques, plants or microorganisms are used to remove metals from soils.

Solubility enhancement by surfactants at various pHs was examined before the experiments on biodegradation. The result showed that the toxic effect of rhamnolipids can disappear in the presence of soil particles and solubility enhancement of phenanthrene does not work for improved mineralization in a soil-water system [55].

The application of inoculants of biosurfactant-producing bacteria in phytoremediation is a new technique to enhance the efficiency of this technology. In phytoremediation, biosurfactants are applied to identify their toxic effects on plants. Usually, biosurfactants are environmentally friendly, but some experiments under certain conditions have shown them to exhibit some toxicity in the environment [40]. However, a cautious use of these compounds will help to improve cleanup of the toxic pollutant in the environment and ensure a clean environment [2].

1.7 Application of Biosurfactant Technology on Contaminated Soils

Remediation of heavy metals pollution

Hong et al. [56] examined the use of saponin, (a plant-derived biosurfactant) to remove cadmium and zinc, from three soil types. The soils used

were Andosol, Cambisol and Regosol. For Cd the rates of removal was 90–100%, while the rate of removal for Zn was 85–98%. An optimum concentration of 3% saponin was required for metal removal within 6 hours and the soil with maximum efficiency was Regosol.

Pseudomonas bacteria produces Rhamnolipid biosurfactants which has been used in soil washing for metals like Cd, Zn and Pb in recent years. Mulligan and Wang [57] studied the removal of heavy metal from sandy soil contaminated with 1710 mg/kg of Cd and 2010 mg/kg of Ni. 0.5% foam solution of rhamnolipid, after 20 pore volumes was able to achieve maximum metal removal efficiency of 73.2% Cd and 68.1% Ni while the removal efficiency for the liquid solution was 61.7% Cd and 51.0% Ni.

Rhamnolipid biosurfactant produced by *Pseudomonas eruginosa* was also evaluated by Juwarkar et al. [58] to know the potential of removing Cd and Pb from contaminated soil. Their results showed that while tap water only removed the mobile fraction from contaminated soil, di-rhamnolipid removed both available fraction of Cd and Pb and the bound metals.

The possibility of using surfactin, rhamnolipid and sophorolipid for Cu, Pb and Zn removal from sediments was studied by Mulligan et al. [59]. 0.5% rhamnolipid was able to remove 65% of the copper and 18% of the zinc in a single wash; 4% sophorolipid removed 25% of the copper and 60% of the zinc while, surfactin removed only 15% of the copper and 6% of the zinc.

1.8 Remediation of Hydrophobic Organic Compounds

The capacity of a rhamnolipid biosurfactant to remove a contaminant called Pentachlorophenol (PCP) (a highly toxic, wood preservative) from soil was investigated by Mulligan et al. [60]. 1000 mg/kg contamination of PCP in fine sand soil and sandy-silt soil, was treated with 1% rhamnolipid; 60% and 61% of PCP was removed from the soils respectively. The biosurfactant removed 36% and 44% of the PCP by volatilization while the rest was removed by other means.

The remediation of hexachlorobenzene (HCB) contaminated soil was proposed using a plant-based surfactant extracted from fruit pericarps of a microorganism called *Sapindus mukorossi*. 90% of the HCB solubility was realized in batch

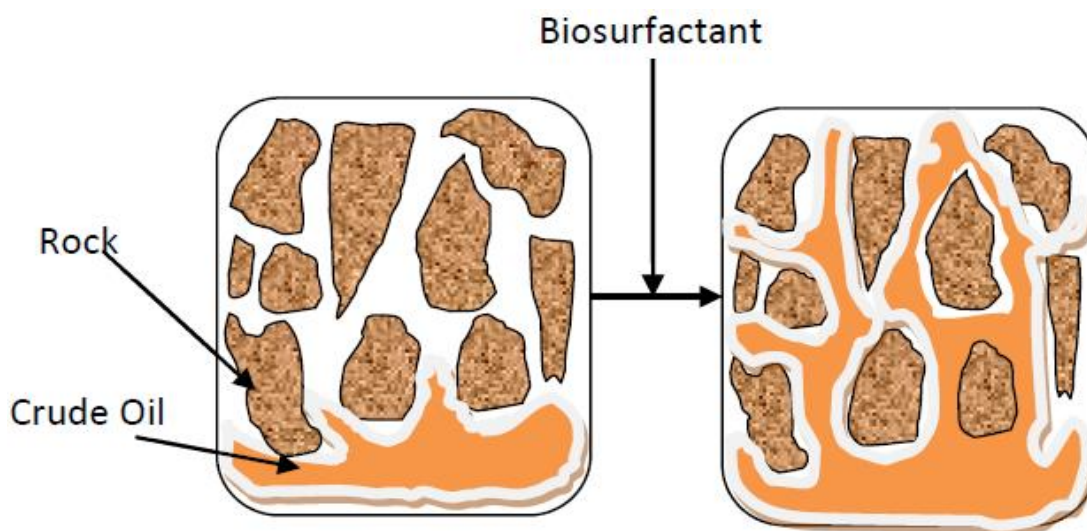


Fig. 3. Application of biosurfactants in microbial enhanced oil recovery [2]

desorption studies for high level soil contaminations; also the HCB recoveries for low level soil contaminations were up to 90% of the total HCB [61].

Biosurfactants have been found to be more efficient in Total Petroleum Hydrocarbon (TPH) removal than synthetic biosurfactants as observed by the experimental results of Lai et al. [62]. When 0.2 mass% of rhamnolipids, surfactin, Tween 80 and Triton X-100, were applied to ca. 3,000 mg TPH/kg contaminated dry soil; 23%, 14%, 6% and 4%, respectively of TPH was realized. When applied to ca. 9000 mg TPH/kg dry soil, the removal efficiency increased to 63%, 62%, 40% and 35%, respectively.

The removal of a gasoline contaminated soil can be achieved by addition of rhamnolipid produced by *Pseudomonas* sp. along with poultry litter [14]. Research with other kinds of microorganism like *Pseudomonas marginalis*, also showed that the produced biosurfactants also solubilized (PAHs) such as phenanthrene and improved biodegradation [63].

The study of sophorolipids effects on phenanthrene biodegradation showed that the concentration of phenanthrene with initial concentration of 80 mg/L within 36 hour in the presence of 500 mg/L reduced to 0.5 mg/l of the surfactant compared to 2.3 mg/L without surfactant in a 10% soil suspension [64]. The microorganism *Sphingomonas yanoikuyae* obtained a maximal degradation of 1.3 mg/L/h

with the sophorolipid instead of 0.8 mg/L/h from fluorescence measurements; the sophorolipids showed improved phenanthrene concentration instead of increased biomass concentration. For concentrations up to 1 g/L the toxicity of the sophorolipid was low. Adsorption of the surfactant to the soil was observed as CMC of the sophorolipid in water increased from 4 mg/L to 10 mg/L in the presence of 10% soil suspensions.

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

The compound used for the experiment, 2,4-dichlorophenol (2,4-DCP), was considerably more degraded when sophorose lipids were added to the soil slurry (Fig. 4). Decrease of 2,4-DCP in the suspensions was found to be generally a slow process for the first 8 days. However, a sharp drop in the suspension was observed afterwards (Fig. 4a, b). In the presence of sophorose lipids, this drop was significantly

deeper as compared to the sample without sophorose lipids.

1.9 Plants or Microorganisms used as Biosurfactants

Natural biosurfactants can be produced extracellularly or as part of the cell membrane by a wide variety of microorganisms such as bacteria, fungi and yeast. Some examples

include *Pseudomonas aeruginosa* which produces rhamnolipids, *Bacillus subtilis* which produces surfactin [65,66], *Nocardia amarae* [67] and *Saccharomyces lipolytica* CCT-0913 [68]. The hydrophobic part is based on long chain fatty acids, hydroxyl fatty acids or α -alkyl- β -hydroxy fatty acids. The hydrophilic group can be a carbohydrate, amino acid, cyclic peptide, phosphate, carboxylic acid or alcohol [69,70].

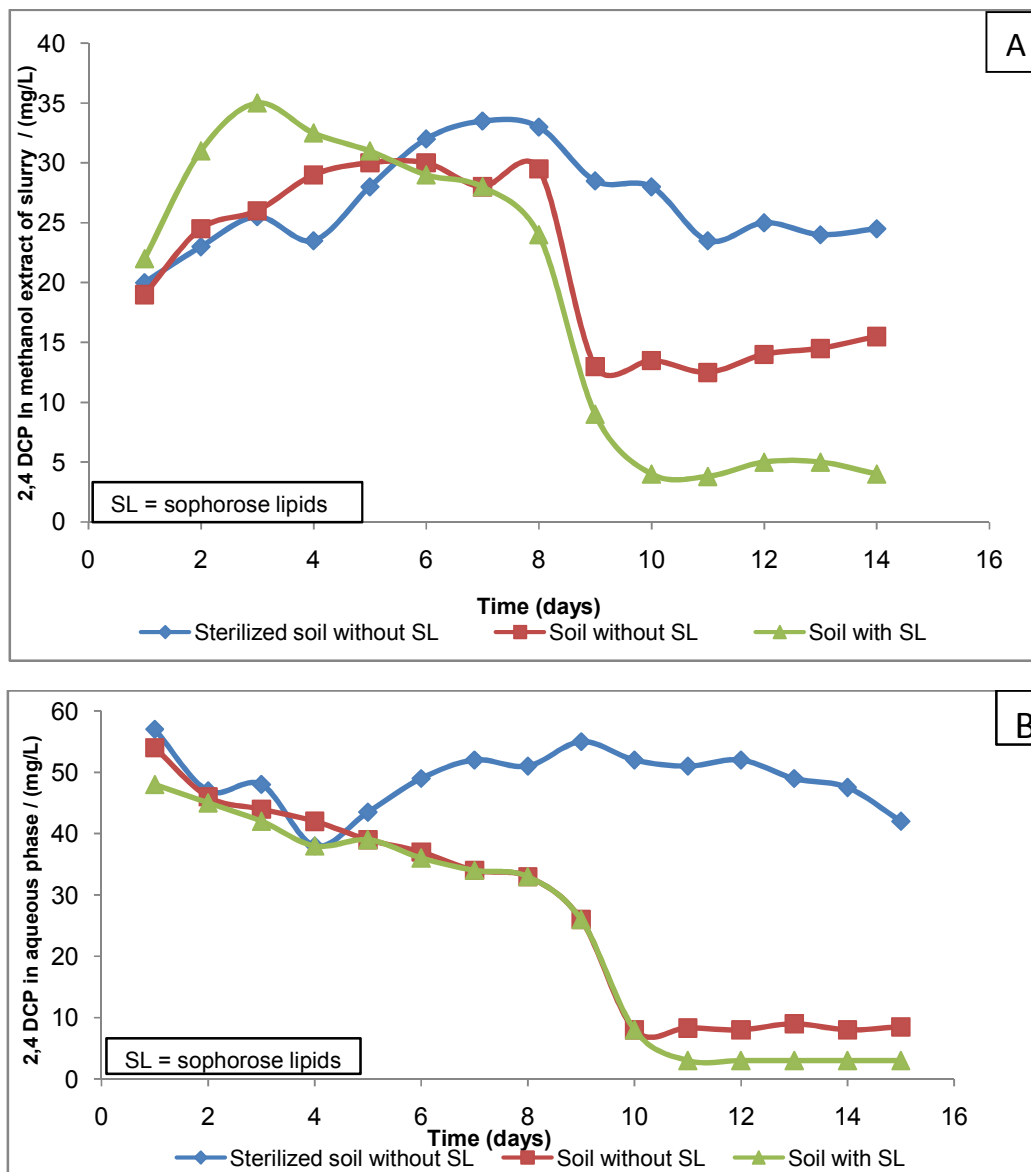


Fig. 4. The effect of sophroselipids on 2,4 dichlorophenol soil suspension: (A) in methanol extract of slurry (B) in aqueous phase (soil 40g; water 60 ml; 2,4 DCP 6g; sophrose 38mg) [13]

1.10 Production of Rhamnolipid from Bacterial Isolates

Biosurfactants are produced by many different bacterial genera. Isolated bacterium was used for the production of biosurfactant by growing the organism in a specific medium. In the study of detoxification of heavy metals by Sinha and Paul [71], biosurfactant production was carried out in water-insoluble medium containing 1.5% (V/V) cooked vegetable as substrate along with MgSO₄·7H₂O, KH₂PO₄, NaNO₃, yeast extract and peptone. The cultures were taken in 500 ml Laboratory flasks with 100 ml of medium. Filter-sterilized trace element solution was added to the medium which was autoclaved and allowed to cool. Then 2 ml of the culture was added to the medium and incubated at 30°C for 48–72 hours [71].

1.11 Advantages of using Biosurfactant in Bioremediation

1. Biosurfactants are readily biodegradable and therefore do not constitute additional pollution threat.
2. Biosurfactants reduce the total time taken for biodegradation of PAHs in contaminated soils.
3. Biosurfactants reduce surface and interfacial tension, thereby increasing the surface areas of insoluble compounds leading to increased mobility and bioavailability of hydrocarbons.
4. Surface active compounds produced by bacterial strains do not need to have survival ability in soils contaminated with heavy metals.
5. They are environmentally friendly, less toxic and non-hazardous.
6. Their production is potentially less expensive than synthetic surfactants and is achievable in situ at the contaminated sites from inexpensive raw materials.

1.12 Disadvantages of using Biosurfactant in Bioremediation

1. There is a relatively high production and recovery cost, as well as the difficulty of their mass production.
2. Prolonged exposure of skin to biosurfactants can cause chafing because surfactants (like soaps) disrupt the lipid coating that protects the skin and other cells.

2. CONCLUSION

Biosurfactants have shown their potential for remediation of contaminated soils by increasing biodegradation rate and reducing contaminant minimum concentration.

Soil and water that are contaminated with organic and inorganic pollutants can be effectively treated with biosurfactants.

The value of CMC determines the ability of biosurfactants to reduce the surface tension and interfacial tension and increase the solubility and bioavailability of hydrophobic organic compounds.

Careful and controlled use of biosurfactants will help to enhance cleanup of toxic environmental pollutants and render the environment clean.

Soils contaminated with heavy metals like Cadmium, lead and zinc have been effectively treated with Rhamnolipids which is produced by *Pseudomonas aeruginosa*.

Biosurfactants possess higher TPH removal efficiency than other substances as observed by experimental results.

Biosurfactants have been shown to enhance biodegradation of hydrocarbons as 2,4-DCP in soil suspension was considerably more degraded when sophorose lipids was introduced into the soil slurry.

Bioremediation is often a longer treatment option and prolonged exposure of biosurfactants to skin can be very harmful.

Biosurfactants have several applications in various industries such as agriculture, petroleum sector–microbial enhanced oil recovery, medicine, pharmaceutical and cosmetic industries.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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