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Bioremediation of Hydrocarbon-Contaminated Environments: Harnessing the Potential of Biosurfactants – A review

Sowbaranika U[1], Ashok Kumar K[1]*, Jayanthi M[1], Abirami G[1], Suganthi M[1], Ling Shing Wong[2], Durgadevi R[1], Prakash B[1], Suresh D[3]

[1]Department of Biotechnology, School of Life Sciences, Vels Institute of Science, Technology and Advanced Studies [VISTAS], Pallavaram, Chennai - 600 117, India
[2]Faculty of Health and Life Sciences, INTI International University, Persiaran Perdana BBN, Nilai 71800, Negeri Sembilan, Malaysia
[3]Department of Microbiology, School of Life Sciences, Vels Institute of Science, Technology and Advanced Studies [VISTAS], Pallavaram, Chennai - 600 117, India

**Corresponding author's E-mail: bioashok2002@gmail.com*

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Abstract

Hydrocarbon contamination from industries like petrochemicals threatens the environment and public health. Benzene, toluene, xylene, and polycyclic aromatic hydrocarbons in petroleum products are highly toxic. Conventional cleanup methods are costly and risk secondary pollution. This review highlights biosurfactants, microbially produced compounds that enhance hydrocarbon degradation by lowering surface tension and increasing bioavailability. Biosurfactants are biodegradable and eco-friendly, making them a sustainable alternative to synthetic surfactants. The review intends to cover the biosurfactant sources, types, mechanisms, and their applications in hydrocarbon-contaminated environments. Recent bioremediation advancements, including microbial-enhanced oil recovery, soil and water cleanup, and heavy metal removal, are discussed. Optimizing biosurfactant production is also explored, offering a green and effective solution to combat hydrocarbon contamination and promote environmental restoration.

Keywords: *Hydrocarbon contamination, biosurfactants, bioremediation, BTX, pollution control.*

1. Introduction

Pollution, driven by the introduction of contaminants into the environment, poses a significant global challenge. Hydrocarbon contamination, arising from the petrochemical industry and other anthropogenic sources, has emerged as a pressing environmental concern. This review article delves into the environmental impact of hydrocarbon pollution and explores the potential of biosurfactants as a sustainable solution for bioremediation.

Pollution

Pollution encompasses the introduction of harmful contaminants into the environment, adversely affecting living organisms and ecosystems. Hydrocarbon contamination, stemming from the petrochemical industry, comprises a major subset of environmental pollutants. Hydrocarbons consist of hydrogen and carbon atoms and can be naturally occurring or anthropogenic. The release of petroleum compounds into the environment, either intentionally or accidentally, has dire consequences, contributing to soil and water pollution (Shallu et al., 2014).

Side Effects of Hydrocarbons

Hydrocarbons, the primary constituents of petroleum, encompass a wide array of compounds, including benzene, toluene, xylene (BTX), and polycyclic aromatic hydrocarbons (PAHs). These substances are known for their toxicity and carcinogenic properties, posing significant risks to human and animal health. Prolonged exposure to BTX compounds can lead to various diseases, including cancer, organ damage, and reproductive issues (Kimura et al., 2020).

Remediation of Hydrocarbons

Bioremediation is a technique that uses microbes or enzymes produced by them which degrade pollutants or xenobiotics (Ekeoma et al., 2023; Pratibha et al., 2023)**.** Conventional methods for hydrocarbon remediation, such as mechanical and chemical approaches, often prove expensive and may result in secondary pollution issues. Surfactants, chemical compounds capable of reducing surface tension, have been used for remediation but suffer from environmental drawbacks. The search for sustainable alternatives to synthetic surfactants has led to the exploration of biosurfactants.

Biosurfactants

Biosurfactants are amphiphilic molecules that reduce surface tension abilities which can be used in environmental, Industrial, agricultural and therapeutic activities and can also play a role in petroleum bioremediation (Markande et al.,2021; Voulgaridou et al., 2021; Singh et al., 2007; Çelik et al., 2021). Biosurfactants are a secondary metabolite of microorganisms that can be processed by cultivating microorganisms that produce biosurfactants in the stationary phase on a variety of inexpensive substrates, such as biochar, plant oils, carbohydrates, wastes, and so on. The regulation of environmental factors and growth conditions can also be used to control the high-level production of biosurfactants (Varjani., & Upasani, 2017; Pornsunthorntawee et al., 2010). Biosurfactants, surfactant molecules produced by microorganisms, have garnered attention as environmentally friendly solutions for hydrocarbon bioremediation. Their capacity to reduce surface tension, low toxicity, biodegradability, and high specificity make them promising candidates for pollution control (Banat et al., 2000).

Biosurfactants: Sources

Biosurfactants are produced by various microorganisms, including bacteria, yeast, and fungi. These molecules exhibit diverse chemical structures and surface properties. Bacteria, particularly Pseudomonas strains, have been extensively studied for biosurfactant production and hydrocarbon degradation (Pokethitiyook et al., 2002; Obuekwe et al., 2009). Biosurfactants increase the degradation of hydrocarbons present in petroleum by enhancing the bioavailability of these contaminations for oleophilic microorganisms present in polluted aquatic environments making the bioremediation process rapid. (Zahed et al., 2022).

Types of Biosurfactants

The surface tension reduction molecules are of two types Biosurfactants are low molecular weight (<1500 Da) substances and Bioemulsifiers are high molecular weight polymers of polysaccharides lipoproteins. polysaccharides, lipoproteins or Lipo-polysaccharides proteins. (Pintu et al., 2023). Table 1 shows the different classes of biosurfactants with examples and microbial sources producing them. These molecules, such as rhamnolipids, sophorolipids, surfactin, and iturin, have unique properties that make them suitable for various applications in pollution control (Ahimou et al., 2000; Daverey et al., 2008).

Table 1: Classes of Common biosurfactants and producing microbes (Pintu et al., 2023)

Class	Biosurfactants	Microorganisms
Lipoproteins	Surfactin	*Bacillus subtilis, Bacillus pumilus A*
	Viscosin	*Pseudomonas fluorescens*
	Lichenysin	*Bacillus licheniformis*
	Anikasin	*Pseudomonas fluorescens HKI0770*
Glycolipids	Rhamnolipids	*Pseudomonas aeruginosa, Pseudomonas putida*
	Trehaloselipids	*Rhodococcus sp., Arthrobacter sp.*
	Sophorolipids	*Candida bombicola, Candida apicola, Candida batistae*
Phospholipids, neutral lipids and fatty acids	Phospholipids	*Thiobacillus thiooxidans*
	Fatty acids	*Corynebacterium lepus*
	Neutral lipids	*N. erythropolis*

Role of Biosurfactants in Bioremediation Process

Biosurfactants play a crucial role in enhancing the natural biodegradation of hydrocarbons. Their ability to emulsify hydrophobic substances, increase water solubility, and decrease surface tension facilitates the removal of oily pollutants from soil and water environments. Applications of biosurfactants in microbial-enhanced oil recovery, soil remediation, heavy metal removal, and aquatic pollution control are explored (Singh et al., 2007).

Biosurfactants enhance the effectiveness of bioremediation by improving the solubility, bioavailability, and accessibility of pollutants to microorganisms. Their environmentally friendly nature and versatility make them promising tools in the development of sustainable and effective bioremediation strategies. Biosurfactants are emulsifiers that lower surface tension. Biosurfactants can be found either intracellularly or extracellularly, where they are secreted from the cells. (Antoniou et al., 2015)

Other Applications

Beyond pollution control, biosurfactants find applications in the food industry as emulsifiers, foaming agents, and antimicrobial agents. Their potential use in pharmaceutical fields and metal chelation processes is also discussed (Hood and Zottola, 1995; Kakugawa et al., 2002; Wang and Mulligan, 2009). Biosurfactants have two functions: they increase surface area, which makes complexes that are insoluble in water more bioavailable, and they bind to heavy metals to enable the removal (Rodrigues et al., 2006). Research has demonstrated the anti-inflammatory, antibacterial, and antioxidant characteristics of biosurfactants (Williams, 2009).

Mechanisms of Biosurfactants

Biosurfactants operate through two primary mechanisms: enhancing substrate bioavailability for microorganisms and increasing cell surface hydrophobicity. These mechanisms promote the mobility and bioavailability of hydrocarbons, leading to enhanced biodegradation and removal (Magdalena et al., 2011).

Factors Affecting the Production of Biosurfactants

Various factors influence biosurfactant production, including the carbon substrate, nitrogen source, and environmental conditions such as pH, temperature, and agitation. Optimizing these factors can maximize biosurfactant yield, making the process more efficient and cost-effective (Laith et al., 2007).

In conclusion, biosurfactants offer a sustainable and eco-friendly approach to addressing hydrocarbon contamination, opening new avenues for pollution control and environmental restoration. Their versatility and biodegradable nature make them a promising solution to mitigate the adverse effects of hydrocarbon pollution on ecosystems and human health.

Recent Advances in Biosurfactant-Mediated Bioremediation

Bioremediation Technologies Utilizing Biosurfactants

Recent developments in bioremediation technologies have demonstrated the effectiveness of biosurfactants in cleaning up hydrocarbon-contaminated environments. Biosurfactant-enhanced bioremediation processes have gained traction due to their ability to accelerate the natural degradation of hydrocarbons, which are hydrophobic and do not readily dissolve in water. Biosurfactants increase the solubility of these hydrophobic compounds by forming micelles or emulsions, making them more accessible to microbial degradation.

Microbial-Enhanced Oil Recovery (MEOR)

MEOR techniques harness the power of biosurfactants to improve oil recovery from reservoirs. By injecting biosurfactant-producing microorganisms into oil reservoirs, biosurfactants are generated in situ, reducing oil viscosity and enhancing oil flow. This method has gained attention in the petroleum industry for its potential to increase oil extraction efficiency (Rahman et al., 2002). The Potential-microorganism-immobilized-ono biochar system is a type of MEOR method integrating with biosurfactants that are produced in in-situ and make the bioremediation process more cost-effective. The biosurfactant production, purification and transportation expenses can be saved by using the PMIBC method which makes bioremediation of petroleum hydrocarbons in contaminated groundwater, lakes, marshes, etc more economical. (Gwenzi et al., 2017; Zhao et al., 2014).

Soil and Water Bioremediation

Biosurfactant-mediated soil and water bioremediation methods have proven successful in cleaning up hydrocarbon-contaminated sites. Microorganisms that produce biosurfactants can effectively degrade a wide range of hydrocarbons, making them valuable tools for restoring polluted ecosystems (Barathi and Vasudevan, 2001; Ojumu et al., 2005).

Heavy Metal Removal

Biosurfactants also play a role in heavy metal remediation by forming complexes with metal ions, enhancing their removal from contaminated soils and water. The use of biosurfactant foam technology, as demonstrated by Wang and Mulligan (2009), offers a promising approach to efficiently remove heavy metals like cadmium and nickel from soil environments. The usage of Biosurfactants derived from plants together with microbial species can be more effective than employing them separately for the bioremediation process (Pintu et al., 2023).

Biosurfactants in Agricultural and Environmental Applications

Improving Soil Fertility

Soils contaminated with hydrocarbons suffer from reduced fertility, affecting local ecosystems. Biosurfactants can emulsify hydrocarbons, increasing their water solubility and aiding in the removal of oily substances from soil particles. This enhancement of soil quality can improve plant growth and agricultural productivity, making biosurfactants valuable tools in sustainable farming practices (Smita, & Dahale., 2015).

Bioremediation of Polycyclic Aromatic Hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs) are persistent pollutants with adverse effects on ecosystems. Biosurfactants from microorganisms, such as Streptomyces species, have shown promise in bioremediating PAH-contaminated soils. Recent studies highlight the potential of biosurfactants to enhance the removal of PAHs, contributing to environmental restoration (Smita, & Dahale., 2015). Researchers from various Canadian institutions studied the creation of a lipopeptide biosurfactant made by Bacillus subtilis N3-1P from fish waste-based peptone as a primary food substrate for this bacterium (Zhu et al., 2020).

Challenges and Future Directions

While biosurfactant-mediated bioremediation holds great promise, several challenges must be addressed. Optimization of biosurfactant production processes, scalability, and cost-effectiveness remain key areas of research. Additionally, the selection of suitable biosurfactant-producing microorganisms for specific applications is crucial. Furthermore, incorporating recent advances in biotechnology, such as synthetic biology and genetic engineering, offers opportunities to enhance biosurfactant production and tailor biosurfactants for specific environmental challenges. The development of efficient biosurfactant-producing strains and sustainable production methods is an ongoing area of innovation (Raza et al., 2020).

4. Conclusion

In conclusion, biosurfactants represent a sustainable and eco-friendly solution for addressing the pervasive issue of environmental hydrocarbon contamination. Recent advancements have highlighted their potential in various bioremediation applications, from enhancing oil recovery to cleaning up polluted soils and waters. Biosurfactants offer an effective means of improving soil fertility, removing heavy metals, and bioremediating persistent hydrocarbon pollutants like PAHs. As global environmental concerns continue to grow, biosurfactant-mediated bioremediation stands as a beacon of hope for mitigating the adverse effects of hydrocarbon pollution. Future research should focus on optimizing biosurfactant production processes, exploring genetic engineering possibilities, and expanding their applications to ensure a cleaner, greener future for our planet.

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