

# A Review on Nanoparticles and Biosurfactants in Wastewater Treatment for Environmental Sustainability

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## Abstract

The world's water is becoming increasingly polluted as both industrial activity and population continue to grow rapidly. There is an urgent need for cleaner and more sustainable methods of water treatment. Conventional physical and chemical purification techniques often fail to effectively remove persistent pollutants such as heavy metals, dyes, oils and emerging organic contaminants. Because of their unique physicochemical properties and high efficiency, nanoparticles and biosurfactants have recently gained attention as eco-friendly alternatives. Nanoparticles including metal, metal oxide, carbon-based and composite materials—possess remarkable surface area, reactivity and catalytic capabilities that enable the removal or degradation of various hazardous substances. Similarly, biosurfactants produced by microorganisms improve pollutant solubilization, emulsification and bioavailability, while maintaining low toxicity and biodegradability. This review paper highlights the structure, advantages and applications of both nanoparticles and biosurfactants in wastewater treatment. It also explains how these materials enhance pollutant removal through mechanisms such as adsorption, photocatalysis, micelle formation and microbial augmentation. The combination of these environmentally friendly solutions offers a highly effective and sustainable approach to addressing modern wastewater challenges and supporting long-term environmental preservation.

**Keywords:** Biosurfactants, Nanoparticles, Wastewater Treatment, Sustainable Development, Hydrophobic organic compounds (HOCs), Carboxymethyl Cellulose (CMC)

## 1. INTRODUCTION

Because of the tremendous population growth and fast industrialization, the contamination of current water supplies has increased globally. <sup>[1]</sup> The world's resources are under threat from the growing global population. The exploitation of two essential resources by human intervention energy and water presents grave risks for both water contamination and global warming. Water is an abundant natural resource on Earth and one of the basic necessities for human survival <sup>[2-4]</sup>. It is employed for household chores, industrial processes, drinking, and more. Water contamination, including the discharge of chemicals, wastewater and toxic effluents into water bodies, is a consequence of the growth in unsustainable urbanization and industrialization <sup>[3-10]</sup>. The majority of nations are currently dealing with severe drinking water issues, particularly in developing nations. Due to prolonged droughts, population growth, stricter health-based regulations and conflicting demands from a range of users, the world is facing significant

challenges in meeting the growing demands for clean water as freshwater supplies are running out <sup>[11, 12, 13]</sup>. Human health depends on clean water, which is defined as water devoid of harmful substances and pathogens. Bacterial contamination of drinking water is the cause of 80 % of diseases in nations like India. Any drinking water should have fecal and total coliform counts of 0 in a 100 ml sample, according to the World Health Organization <sup>[14]</sup>. Heavy metal ions and dyes are the two main types of pollutants. It is very hard to fully treat water once these heavy metal ions get into it <sup>[15]</sup>. These pollutants in the water are dangerous for all living things and have a big effect on ecosystems. So, these pollutants need to be removed from dirty water to keep them from hurting people and the environment. At the moment, water supply entrances are dealing with a lot of different problems. About 780 million people around the world don't have access to clean drinking water <sup>[16]</sup>. Urgent action is needed in the impacted areas, which are primarily poor nations where wastewater management is typically nonexistent. Nonetheless, current technology and wastewater management are improving their capacity to supply adequate clean water to meet environmental and human needs. Opportunities for the development of better water resources and arrangements are suggested by recent developments in nanoscience and nanotechnology <sup>[17,18]</sup>. In comparison to massive infrastructure, it is anticipated that the incredibly efficient, integrated and multifunctional advancements made possible by nanoscience and nanotechnology will provide high rates of performance and reasonable and economical wastewater treatment solutions <sup>[19]</sup>. It is essential to remove these pollutants using effective and eco-friendly techniques <sup>[20,21]</sup>. In existing studies, various approaches have been implemented for treating wastewater, including solvent extraction, ultrafiltration, evaporation and reverse osmosis. Nevertheless, these methods extract contaminants from water without converting them into harmless byproducts <sup>[22]</sup>. Complete mineralization can be readily accomplished through chemical or photochemical oxidation <sup>[23]</sup>. The aim of every oxidative method is to produce and utilize a hydroxyl free radical as a potent oxidizing agent to mitigate the impact of pollutants. Once activated, hydrogen peroxide can serve as an oxidizing agent, whether through UV radiation, as a metal ion, or in the form of a Fenton reagent. <sup>[24]</sup>

Nanomaterials are mostly used to fix big problems with water and wastewater. A nanomaterial is a nanometer, which is a trillionth of a meter <sup>[25]</sup>. Nanomaterials are used a lot in biomedicine and pharmaceuticals, electronics and optoelectronics, the clothing industry and cosmetics. These tiny nanomaterials change the physical properties of the material in a number of ways, such as by increasing the volume to surface area ratio and changing the size of the particles based on quantum properties. Nanoparticles have very different properties than regular materials. For example, their magnetic, visual and electrical properties are very different from those of regular materials. Nanomaterials are known for having properties like high adsorption, catalytic activity and reactivity <sup>[26]</sup>. In the last few decades, nanoparticles have gotten a lot of attention and have been used successfully in many areas, such as biology, sensing, medicine, catalytic chemistry and ongoing research and development <sup>[27,28]</sup>. Nanoparticles are frequently employed in wastewater treatment <sup>[29,31]</sup>. Because nanoparticles have a lot of surface area and are very small, they can strongly adsorb and react <sup>[32]</sup>. Many pollution sources around the world have been found to have broken down into different types of nanomaterials, such as bacteria, new pollutants, organic pollutants and inorganic anions <sup>[33,34]</sup>. Nanoparticles, such as carbon nanotubes, zerovalent nanoparticles, metal oxide nanoparticles and nanocomposites, show promise for use in various wastewater ecosystems <sup>[35-36]</sup>. Nanomaterials offer innovative approaches that enhance current water supply systems and unconventional water sources. In the last few years, a number of new ways to clean up wastewater have been made <sup>[21,30,31,37]</sup>.

Biosurfactants are composed of two main components: a hydrophilic part, which can be an acid, peptide, cation, anion, or carbohydrate (mono-, di-, or polysaccharide) and a hydrophobic part, which typically consists of fatty acids or hydrocarbon chains that can be either saturated or unsaturated. Biosurfactants play the crucial role for the wastewater treatment because they have improved the removal of various contaminants through various methods. Because it can aid by the emulsification and solubilization of hydrophobic materials like oils and greases, they are particularly helpful to the cleaning of industrial effluent. Additionally, they are promoting the adsorption of contaminants onto microbial cells, biosurfactants boost the efficiency of biodegradation processes. They can also help break down organic pollutants into like phenols and detergents and mobilize heavy metals. Because these are biodegradable, less toxic, and often produced for renewable resources, biosurfactants are a more sustainable wastewater treatment option than the traditional methods. Their ability to do boost microbial activity and promote the formation of biofilms further emphasizes their potential to offer effective and they have sustainable methods for treating contaminated water.

### 1.1 Wastewater

Wastewater is those type of liquid waste that contains a lot of harmful substances, such as organic matter, bacteria, soluble inorganic chemicals and possibly dangerous heavy metals. These pollutants can change the chemical, biological and physical properties of pure water in a big way. There are two kinds of wastewater is municipal and industrial. Municipal wastewater often contains human waste like feces and urine etc. Industrial and agricultural wastewater, on the other hands, comes from different manufacturing processes i.e., contain both organic and inorganic substances. Heavy metals, radionuclides and trace elements are some of the dangerous things that can be found in wastewater. There are also big microorganisms like bacteria, viruses and protozoa. Wastewater is one of the main causes of diseases that spread through water, especially deadly ones like cholera and typhoid. Wastewater treatment is very important these days because pathogens can be harmful and pollution from wastewater can be dangerous for people, plants and animals. Wastewater treatment should be done by both individuals and governments to keep the environment clean. Physical, chemical and biological processes can be used to clean up waste water and get rid of different kinds of dirt. Wastewater has many different physical properties, including total solids, dye and other substances that can be fixed, volatile, dissolved or suspended [38]. Dissolved materials in wastewater, or total dissolved solids, may include small amounts of organic molecules as well as inorganic salts and metals like sodium, potassium, calcium, magnesium and bicarbonates. For dissolved solids, the sizes of the particles range from 0.01 to 1.00  $\mu\text{m}$  [39,40]. There are three types of chemical contaminants in wastewater: organic, inorganic gaseous. Proteins, carbohydrates fats and oils usually make up 50 %, 40 % and 10 % of the organic pollutants in wastewater, respectively [41]. Wastewater contains organic pollutants such as primary impurities, surfactants and other impurities [42]. Chemical oxygen demand and biological oxygen demand are the best ways to tell how bad organic pollutants are in water. Wastewater has a lot of inorganic pollutants in it, like nitrogen compounds, heavy metals, phosphorus trace elements and other toxic inorganic parts. Wastewater has biological properties in addition to chemical and physical ones. Biological pollutants are living microorganisms that cause disease that are found in wastewater. Bacteria, viruses and protozoa are the main microorganisms in wastewater. They can cause both short-term and long-term health problems.

### 1.2 Nanoparticle for Wastewater Treatment

Nanoparticles are the core of nanotechnology. Nanoparticles are incredibly tiny particles with a size of

less than 100 nm and can comprise carbon, metal, metal oxides, or organic substances <sup>[43]</sup>. Nanoparticles exhibit significant adsorption reactivity and capacity due to their small size and extensive surface area <sup>[44]</sup>. Numerous types of nanomaterials have been reported globally to effectively disintegrate various contaminants, including inorganic anions, organic pollutants, emerging pollutants and bacteria <sup>[45,46]</sup>. Nanoparticles, such as zerovalent nanoparticles, carbon nanotubes (CNTs), nanocomposites and metal oxide nanoparticles (MNPs), are promising tools for use in different types of wastewater ecosystems <sup>[47,48]</sup>. The nanoparticles are made to attract water and are very porous, so they soak up water like a sponge while keeping dissolved salts and other impurities out. The membrane has hydrophilic nanoparticles in it that keep organic compounds and bacteria from getting in, which is more likely to happen with regular membranes over time <sup>[49]</sup>.

Wastewater treatment uses different kinds of nanoparticles. Nanomaterials are important for making technology that has to do with wastewater better. Treatment and removal of pollutants, because they have a lot of surface area, are reactive and other characteristics <sup>[50]</sup>. This section introduces the main nanomaterials that are commonly used in the Carbon-based and Metal and Metal Oxide Nanoparticles are some of the things that are used to treat wastewater. Nanomaterials (like carbon nanotubes and graphene), nanocomposites and hybrid materials others.

### 1.2.1 Metal and Metal Oxide Nanoparticles

The Metal and Metal oxide nanoparticles are used for treating wastewater treatment because they have a large surface area and they are also reactive, adsorbed or catalyze pollutants. These nanoparticles are most effective at getting rid of heavy metals, organic pollutants and bacteria that cause disease.

- **Silver Nanoparticles (Ag-NPs)** it exhibit potent antimicrobial properties; they indicate their efficacy in the treatment of wastewater contaminated with microbes <sup>[51]</sup>. They have also reported to remove water pollutants like arsenic metal from contaminated water sources <sup>[52]</sup>.
- **Gold nanoparticles (AuNPs)** they are less commonly used than silver nanoparticles, but they can help break down organic compounds and have exhibit promise in getting rid of harmful dyes <sup>[53]</sup>.
- **Iron-based Nanoparticles** they are zerovalent iron (ZVI), they used to get removed of lower the levels of pollutants like chromium, arsenic and lead. When there are dangerous types of contaminants present, ZVI nanoparticles are especially helpful in the reductive operation <sup>[54,55]</sup>.
- **Titanium Dioxide (TiO<sub>2</sub>) Nanoparticles** they are particularly regarding their photocatalytic properties under ultraviolet light, has emerged as a prominent area of research in recent years. TiO<sub>2</sub> can get rid of dyes, phenols and other organic pollutants. It can also be used to clean up industrial and municipal sewage <sup>[56,57]</sup>.
- **Zinc oxide Nanoparticles (ZnO)** can be used to clean up the wastewater treatment because they can kill germs and breakdown heavy metals and organic pollutants. They are also made using green methods from natural materials like plant extracts. This is cheap and good for the environment, which makes them a promising long-term solution for cleaning up wastewater.

### 1.2.2 Carbon-based Nanomaterials (Nanotubes, Graphene)

The Carbon-based nanomaterials, such as CNTs and graphene, are used to treat wastewater treatment because they have properties like high surface area conductivity and the ability to adsorbed.

- **Carbon Nanotubes (CNTs)** they are appropriate substrates for the adsorption of various contaminants, including heavy metals, organic compounds and pharmaceuticals <sup>[58]</sup>. They are good for treating water because they have a large surface area and a structure that lets water through more easily <sup>[59]</sup>.

- **Graphene and Graphene Oxide (GO)** have proven to be highly effective in demonstrating various pollutants, including dyes, oils and metals. Graphene oxide is an important material for water processing because it has a large surface area, reversible surface chemistry and the ability to change its surface <sup>[60,61]</sup>.
- **Graphene-based hybrid materials** they are combine graphene with other materials like polymers or metals, also work better at getting rid of other pollutants, especially organic ones and heavy metals <sup>[62]</sup>.

### 1.2.3 Nanocomposites and Hybrid Materials

Nanomaterials combines with the polymers, natural materials or metal oxides are the also known as nanocomposite materials and they provide better performance in wastewater treatment plants. When they compared to single nanomaterials, type of nanomaterials typically provides improved stability, recyclability and pollutant removal capabilities.

- **Polymer based nanocomposites** they are superior mechanical strength, stability and adsorption, nanocomposites are frequently used to treat wastewater. Organic pollutants can be the photo catalytically degraded by TiO<sub>2</sub>/polymer composites, which are hybrid composites of TiO<sub>2</sub> and polymers <sup>[63,64]</sup>.
- **Magnetic nanocomposites** they fall under the Dissolved Air Flotation type, have the benefit of being simple to separate from treated water. For instance, a very efficient and sustainable way to remove organic pigments and heavy metals is to combine iron oxide nanoparticles with activated carbon <sup>[65,66]</sup>.
- **Graphene-based Hybrid Materials** the graphene oxide and polymers or other useful substances interact synergistically, graphene oxide-based hybrid materials have shown a great potential for the degradation of organics, oil and dye <sup>[62]</sup>.

### 1.2.4 Other Emerging Nanomaterials

Apart from extending their research on the above-studied materials, several other prospective nanomaterials that are in the development process accept in wastewater treatment. Usually, such materials provide the properties which can be interesting for types of pollutant removal.

- **Nanofibers** have been widely employed in water filtration because they possess large surface area and pore volume. Polymer nanofibers, including polyvinyl alcohol (PVA), may be particularly valuable for filtering organic compounds and heavy metals from industrial water residues <sup>[66]</sup>.
- **Nanostructured Membranes** that are derived from silica or graphene oxide are employed in higher level of filtration. Many of these membranes can filter fine particles, organisms dissolved substances as well.
- **Metal-Organic Frameworks (MOFs)** are a new kind of porous material they have been found to possess wonderful adsorptive capability for various pollutants such as heavy metals, dyes and oils. Still, MOFs have highly ordered and adjustable pore systems that are used for selective adsorption in wastewater treatment <sup>[67,68]</sup>. Different forms of nanomaterial include above where each form is more favorable for the removal of pollutants in wastewater. Problems related to water pollution can be solved by using metal and metal oxide nanoparticles, carbon-based materials, composites and some new materials. But despite these advantages, there is still some issues associated with material stability, material costs and possible impacts on environment that must be solved to introduce these technologies into practices.

## 1.3 Mechanism of Nanoparticle – Based Wastewater Treatment

- **Nano adsorbents:** The organic or inorganic nanoparticles with a high affinity for adsorbing substances

are used to many kinds of treatment. These adsorbents can effectively remove a wide range of contaminants.<sup>[69]</sup> The ideal adsorbent is small, has a large surface area, good catalytic capacity and high reactivity. Metallic nanoparticles, nanostructured materials, nanostructured mixed oxides and metallic oxide nanoparticles are the four types of nano adsorbents distinguished by their adsorption mechanism <sup>[70]</sup>.

- **Nano catalysis:** Photocatalytic processes which would comprise the mix of This treatment uses visible light and metallic nanoparticles. In the Photocatalytic reactions with hydroxyl radicals destroy microorganisms. Both organic substances and organisms (bacteria). Non-organic substances like semiconductors and metal oxides are frequently used in nano catalysts. <sup>[71,72]</sup>
- **Nanomembranes** can remove contaminants from wastewater in this treatment. Heavy metal ions, dyes and other pollutants are commonly removed with these. Nanotubes, nanoribbons, & nanofibers are examples of nanomembranes that are commonly employed. Nano particles have antimicrobial agents used in the water treatment with high bacterial contamination levels. Silver nanoparticles & graphene-oxide nanoparticles have two roles one in biofouling reduction (disable bacterial cells) and microbial attachment reduction by producing a strong water layer due to its hydrophilic nature. Furthermore, research on nanomaterials such as carbon nanotubes, graphene, metal organic frameworks, molybdenum disulfide, covalent organic frameworks and aquaporin has been used successfully for saltwater desalination. Nanomaterials are widely used in the membrane for reverse osmosis (RO), forward osmosis (FO), nanofiltration (NF), membrane distillation (MD) and capacitive deionization (CDI). <sup>[73]</sup>

#### 1.4 Biosurfactants for wastewater treatment

The biological method synthesis of nanoparticles plays a vital role among the research scientists. The major advantages of a biological method like cost-effectiveness, eco-friendly and so on, influences the biosynthesis of nanoparticles. Some of the organisms possess biosurfactants, which acts as a substitute for the chemical synthesis of nanoparticles <sup>[74]</sup>. Biosurfactants are the emulsifiers, which help to decrease the surface tension of the compound. It is accessible in the intracellular and extracellular part of the bacterial cell. It is comprised of hydrophobic and hydrophilic moieties, which helps in the reduction of surface tension of compounds and leads to easy degradation by the bacteria <sup>[75]</sup>. Biosurfactants are biological substances derived from microorganisms that possess surface-active properties and can effectively replace commercial surfactants <sup>[76]</sup>. They have a lower critical micelle concentration (CMC) than synthetic ones and, at very low concentrations, significantly reduce the surface tension of oil-water or air-water interfaces <sup>[77,78]</sup>. There some properties of biosurfactants make a great choice for the emulsifications and froth stabilizations. Microbial surfactants they are superior to chemical ones in terms of biodegradability, mild production conditions, ecological compatibility, lower toxicity, higher selectivity and explicit action over extreme temperatures, pH and salinities etc <sup>[79,80,81]</sup>. They promote their application across a range of industries. Hydrophobic organic compounds (HOCs) are effluents are causing the natural aquatic ecosystem to the continuously deteriorate. The discharge of HOCs into the aquatic environment has a significant impact on the quality of water bodies, which in turn affects aquatic life and humans <sup>[82]</sup>. Hydrocarbons and their derivatives, polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyl's (PCBs) are examples of extremely dangerous HOCs that could endanger aquatic life as well as people. The hydrophobic component of HOCs lowers their bioavailability <sup>[83]</sup>. As a result, it is challenging to appropriately degrade or remove HOCs from contaminated water. Historically, wastewater treatment plants have used surfactants to remove HOCs from their effluents. By the reducing of the surface tension

between water and non-polar pollutants, the surfactants increase the bioavailability of HOCs. Nevertheless, employing synthetic surfactants to eliminate HOCs still presents a risk to the environment because they have derived from fossil fuels [84]. The different strategy is simple, economical, environmentally friendly and effective is desperately needed to address the issues surrounding the removal of the HOCs from water bodies. The growing concern for sustainable development that has fundamentally changed how the industries operate. The replacement for synthetic surfactants with biosurfactants is one of the revolutionary steps in developing green technologies that simply rely on renewable resources [85]. Bio-reclamation of water bodies effectively removes or breaks down pollutants and is also environmentally beneficial. The switch from synthetic surfactants to biosurfactants was initially slowed by the prohibitive cost of producing biosurfactants [86]. By growing bacteria that produce biosurfactants on organic waste, this problem was resolved. The value-adding of low-value organic materials has reduced the amount of waste disposed of from various industrial sources [87]. The technique replaces synthetic surfactants with organic waste to eliminate HOC from aquatic environments.

There are very some reviews of biosurfactants as the surface-active agents that cover various substrate sources as well as production and separation methods. However, it should be mentioned that the application of biosurfactants as agents for wastewater treatment has not been examined. In order to support green technologies and replace conventional surfactants, which are derived from petrochemicals and pose a major environmental risk, this study is kind to address the use of biosurfactants for wastewater treatment. They explain the characteristics of biosurfactants, how they interact with wastewater and pollutants, the substrates used to make biosurfactants, how to cultivate microorganisms that produce biosurfactants and how to separate biosurfactants from media. It primarily discusses how they are effectively broken down and eliminate the impurities from wastewater. The review study first discusses the characteristics of biosurfactants that contribute to the features of wastewater treatment. It also explains the mechanisms of interaction between biosurfactants and wastewater for the removal of contaminants and covers performance-defining criteria such as emulsification index, critical micelle concentration and surface tension. The synthesis of biosurfactants from different sources both organic (including waste material) and inorganic is thoroughly reviewed and presented here to help researchers understand the scope of biosurfactant production on an industrial scale and to provide insights into the development of the technology. The effectiveness of biosurfactants in degrading and removing pollutants, such as heavy metals and lipophilic components, from wastewater generated by industrial, residential and agricultural processes is also studied. Finally, the discussion of biosurfactant limitations in wastewater treatment increases the application of biosurfactants as an environmentally friendly technology in wastewater treatment procedures.

### 1.5 Characteristics of surface – active agents

**Hydrophilic-lipophilic Balance (HLB):** It is indicative of hydrophilic or lipophilic characteristics of the surfactants. HLB scales from 0 to 20 units and the surfactant's nature depends on these values. Surfactants with HLB values in the range of 3.5 to 6 have a stronger affinity towards water-in-oil (W/O) emulsions. In contrast, for oil-in-water (O/W) emulsion, the HLB values are higher, ranging from 8 to 18. HLB values are determined empirically or based on the molecular structure of the emulsion. HLB values help in the selection of the emulsification system for the surfactants to be as emulsifiers, foaming agents, detergents and wetting and spreading agents [88].

### 1.5.1 Biosurfactants CMC: definition and relevance

The concentration above which surfactants form micelle is known as CMC. The CMC value of surfactants indirectly reveals the quantity of surfactant required to remediate the contaminant. The lower the CMC, the lower the quantity of surfactant required to form micelle, which increases the bioavailability of the contaminant [89]. Biosurfactants' CMC value decides the pathway through which biosurfactants degrade or remove HOCs from the water entities [90]. the surfactant molecule and the formation of micelles above critical micelle concentration and also represents the changes associated with physical properties such as surface and interfacial tension [91].

### 1.5.2 Types of Biosurfactants

**Glycolipids** Chemically produced surfactants are usually classified according to their polarity, whereas biosurfactants are frequently described according to their chemical makeup and microbiological origin. Glycolipids are carbohydrates joined to hydroxylaliphatic or long-chain aliphatic acids by an ester group. Most biosurfactants are composed of glycolipids. The most well-known glycolipids are sophorolipids, trehalolipids, rhamnolipids [92]. The origins and traits of the different glycolipids were discussed in the section below:

- **Rhamnolipids** they are glycolipids that are created by joining of one or two rhamnose molecules to one or two hydroxydecanoic acid molecules. They well-studied biosurfactant is the primary glycolipid produced by the *P. aeruginosa* [93].
- **Trehalolipids:** These are associated with most *Mycobacterium*, *Nocardia*, and *Corynebacterium* species. Trehalose lipids from *Rhodococcus erythropolis* and *Arthrobacter* species decreased the surface and interfacial tension in culture broth from 25–40 and 1–5 mNm, respectively [94].
- **Sophorolipids:** These glycolipids are produced by yeasts and consist of a dimeric carbohydrate called sophorose and a long-chain hydroxyl fatty acid joined by a glycosidic bond. At least six different hydrophobic sophorolipids are frequently combined to form sophorolipids [95]. The lactone form of the sophorolipid is favored for numerous applications [96].

**Lipoproteins and lipopeptides** they are created by joining a lipid to a polypeptide chain [97]. A variety of viruses, bacteria, algae and fungi have been shown to be susceptible to the antibacterial activity of several biosurfactants. [98,99] demonstrated the antifungal and antibacterial properties of iturin, a lipopeptide produced by *Bacillus subtilis*. With a pH of 5–11 and a six-month shelf life at -18°C, iturin from *B. subtilis* was demonstrated to remain active even after autoclaving [100].

**Surfactin:** The cyclic lipopeptide surfactin, one of the most powerful biosurfactants, is composed of a fatty acid chain connected by a lactone bond to a seven amino acid ring structure [101]. Previous studies have documented a number of physic-chemical properties of surfactin from *B. subtilis*. They found that surfactin can reduce the surface and interfacial tensions of water. Herpes and retrovirus have also been demonstrated to be rendered inactive by surfactin.

**Lichenysin:** Similar to surfactin, *Bacillus licheniformis* produces a variety of biosurfactants that exhibit exceptional stability in high pH, temperature and salt conditions. Lichenysin from *B. licheniformis* may reduce the surface tension and interfacial tension of water to 27 and 0.36 mN m<sup>-1</sup>. [102]

**Phospholipids, Neutral lipids and Fatty acids:** Many bacteria and yeast produce large amounts of fatty acids and phospholipid surfactants when they grow on n-alkanes. *Acinetobacter* spp. 1-N produce phosphatidyl ethanolamine-rich vesicles that create optically transparent micro-emulsions of alkanes in water. These biosurfactants are essential for medical applications. The phospholipid protein complex deficit is the main cause of respiratory failure in prematurely born infants [102]. Furthermore, they have

suggested utilizing the identification and cloning of the genes responsible for the fermentative productions of these surfactants.

**Polymeric biosurfactants** emulsan, liposan, alasan, lipomanan and they are different polysaccharide-protein complexes are among the most studied polymeric biosurfactants. Emulsan is an effective emulsifying agent for hydrocarbons in water, even at concentrations as low as 0.001–0.01% [103]. Liposan, an extracellular water-soluble emulsifier composed of 83% carbohydrates and 17% protein, is produced by *Candida lipolytica* [104,105]. The uses of liposan, a Polymeric biosurfactant, as an act emulsifier in the food and cosmetic industries. [105]

**Particulate biosurfactants** are essential for microbial cells to absorb alkanes because they partition extracellular membrane vesicles to form a microemulsion. The vesicles of *Acinetobacter* spp. Strain HO1-N have a diameter of 20–50 nm and a buoyant density of 1.158 cubic g cm. They are composed of protein, phospholipids and lipo-polysaccharide. [105-106]

### 1.5.3 Mechanism of Biosurfactants

By lowering the surface tension at their interface, biosurfactants enhance the surface interactions between polar and non-polar substances. Because these biosurfactants are the amphiphilic, they can bind to their hydrophilic head to the water at the interface and their hydrophobic tail to the non-polar compounds. As a result, HOCs' bioavailability increases to a point where removal or degradation is feasible. There are the three processes mobilization, solubilization, or emulsification allow biosurfactants to increase the bioavailability of HOCs in a water system. [107]

**Mobilization** When the concentration of the biosurfactant is lower than its CMC, mobilization takes place. In these conditions, the biosurfactants reduce the surface tension (ST) at the interface between two opposing entities. This will improve surface interactions because biosurfactants are amphiphilic. [108] Consequently, bioavailability will increase until the pollutant is easily removed or degraded.

**Solubilization:** When the concentration levels surpass CMC values, biosurfactants start to form micelles with HOCs. A similar structure composed of non-polar materials and biosurfactants that form in a polar environment is called a micelle. Biosurfactant hydrophobic tails allow hydrophobic molecules to be contained within the micelle. Aquatic conditions may expose to the polar heads of surfactants [107]. When the micelles, vesicles and bilayers form at concentrations greater than CMC, the bioavailability of HOCs is greatly enhances.

**Emulsification:** The HOCs are more widely dispersed as tiny droplets in the aqueous phase when biosurfactants are present in the mixture. The emulsification of biosurfactants increases the bioavailability of non-polar compounds in the polar environment, much like mobilization and solubilization. Among all biosurfactants, high molecular weight biosurfactants are the most effective emulsifying agents [109].

### 1.6 Process Defining Parameters

**Surface Tension:** Lowering the surface tension of water is the main goal of adding biosurfactants to the polar/non-polar mixture. The interaction between two opposing entities is improved by the decrease in surface tension. The hydrophobic and hydrophilic compounds are drawn together at their interface by the supplied biosurfactants, making them accessible for removal or degradation from the water bodies [82].

**Emulsification Index (EI24):** The Emulsification Index (EI24) measures how well biosurfactants can form hydrophobic moiety emulsions in hydrophilic environments. For higher values of EI24, which are typically expressed in percentages, the emulsification nature of biosurfactants is more. After adding the biosurfactants to the oil-water mixtures, the values of surface tension and EI24 show what kind of

mechanism the biosurfactants start to make contaminants available for their degradation <sup>[110]</sup>.

### **1.7 Relevance of Biosurfactants and Nanoparticles in Wastewater Treatment**

Wastewater from industrial, agricultural and residential sources can contain chronic contaminants like heavy metals, organic compounds, oils and greases, colors, fertilizers, medications and pathogens. Conventional methods often fail to effectively remove these pollutants. Two modern environmentally beneficial technologies, biosurfactants and nanoparticles, are increasingly recognized for their superior ability to degrade, adsorb, or change pollutants due to their high surface activity, catalytic potential and adjustable physicochemical features. This review covers the primary applications of both techniques in wastewater treatment.

**Improved the Bioavailability and Solubilization of Hydrophobic Pollutants** - By the lowering surface/interfacial tension and creating micelles, biosurfactants increased the solubility of hydrocarbons, PAHs, phenolic compounds, oils and greases. This enhanced microbial decomposition example Rhamnolipids and lipopeptides are especially helpful because they are speed up the breakdown of pollutants that microbes would to otherwise find difficult to the access.

**Enhanced Biodegradation of Organic Contaminants**- Biosurfactants aid microbes and enzymes by improving substrate accessibility and activities. Examples include the use of biosurfactants from a *Stenotrophomonas* sp. To degraded PAHs and TPH by 70–90 % and the rhamnolipid assisted laccase degradation to remove up to 65 % of Bisphenol A.

**Adsorption Improvement and Dye Elimination**- They changing the surfaces adsorbents, biosurfactants improve the dye bindings. 93% of the methylene blue was eliminated by the rhamnolipid-coated with iron oxide nanoparticles.

**Oil and Water Separation Biosurfactants**- They disperse oils, split emulsions and mobilize hydrophobic pollutants. The Rhamnolipids achieve dispersion the efficiencies of up to 100% at optimal pH, 71% of the oil and grease and 80 % of the SCOD were eliminated by anaerobic treatment with surfactin assistance.

**Heavy Metal Removal Biosurfactants**- Chelate metal ions through the complexation, micelles encapsulation and electrostatic interactions. Examples include the removal of 30–80 % of Zn and Cu using *Candida tropicalis* biosurfactants and 85 % of Cd<sup>2+</sup> using rhamnolipid-modified biomass.

**Removal of Heavy Metals**- Nanoparticles have a high adsorption capacity due to their vast surface area and reactive sites. Mechanisms include chemical reduction, bioprecipitation and adsorption. Zerovalent iron nanoparticles are used to the demonstrate nearly the 100 % metal removal.

**Organic Pollutant Degradation**- When UV light exposed nanoparticles degraded persistent organics, especially TiO<sub>2</sub> and ZnO, through the catalytic degradation and photocatalysis.

**Elimination of Pathogens and Disinfection**- Some nanoparticles have the strong antibacterial qualities because they have harmed microbial cells. AgNPs, ZnO and CuO are useful nanoparticles. They help eliminates bacteria, viruses and protozoa to the immune help by many different medicines.

**Removal of Nutrients**- Nanoparticles help with nitrate reduction (nZVI converts NO<sub>3</sub><sup>-</sup> to N<sub>2</sub>) and phosphate adsorption using Fe<sub>3</sub>O<sub>4</sub>, TiO<sub>2</sub> and other metal oxides.

**Oil Spill Remediation**- Nanomaterials enhance microbial hydrocarbon breakdown and offer efficient oil absorption and recovery.

### **Conclusion:**

Ensuring access to clean and safe water remains one of the most pressing global challenges, particularly in the context of rapid industrialization, population growth and increasing contamination of natural water

bodies. The integration of nanoparticles and biosurfactants into wastewater treatment represents a significant advancement towards sustainable and efficient remediation technologies. Nanoparticles, owing to their high surface area, tunable surface chemistry and exceptional catalytic and adsorption capabilities, have demonstrated substantial potential in the removal of heavy metals, dyes, organic pollutants and pathogenic microorganisms. Their incorporation into membranes, photocatalytic systems and the adsorbents has enabled the development of highly effective treatment processes capable of addressing both conventional and emerging contaminants. Biosurfactants, as environmentally compatible surface-active molecules, further enhance treatment processes by improving the solubility, mobility and biodegradability of hydrophobic pollutants. Their low toxicity, biodegradability and effectiveness at minimal concentration make them particularly attractive alternatives to petrochemical-based surfactants. Their ability to enhance microbial degradation and facilitate pollutant removal underscores their importance in modern eco-friendly treatment strategies. Collectively, these innovative materials offer complementary benefits and provide a strong foundation for the advancement of sustainable wastewater treatment technologies. Although challenges persist- such as production scalability, cost reduction and long-term environmental assessment- the continued development of nanoparticle- and biosurfactant based systems holds considerable promise. Continued research and interdisciplinary collaboration will be essential for optimizing these technologies and ensuring their safe and effective application in meeting future water quality demands.

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