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Biosurfactants in Nanotechnology: A Gateway to Green and Sustainable Synthesis of Nanoparticles

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ABSTRACT:

Nanotechnology finds its use in variousapplications across various industries and fields, revolutionizing our approachtowards scientific research, product development and problem-solving.This is deals with nanoscale (<100nm) dimensions particles. Because of its remarkable potential it being one of highly exploited technology now a day.Therefore, nanotechnology has emerged as a promising avenue for addressing environmental pollution concerns. Previously synthetic surfactants were used as nanoparticle stabilizing agents. . As chemically synthesized surfactants were neither cost effective nor environment friendly, biosurfactants are now gaining popularity as a green alternative to synthesize and stabilizevarious nanoparticles. Biosurfactants are biomolecules that are produced by various microorganisms including fungi, yeast, some bacteria etc. They exhibit remarkable properties that make them effective tool not only in the bioremediation but also for the upcoming coming nanotechnology. Owing the excellent properties such asbiodegradability, amphipathic nature, emulsifying activity, biological origin and non-toxicity, it has been gained a significant attention in recent years.In addition,biosurfactants play crucial role in facilitating the production and stabilizationof nanoparticles. The current review focus on green-synthesis of nanoparticles using various biosurfactants and related microbial agents.

Introduction

Nanoparticles are very tiny particles with size varies between 1 to 100 nm. In recent years, the utilization of nano-particles has tremendously increased in the fields of agriculture, disease treatment, gene therapy, microscopy, sensing and in various industries such as pharmaceuticals, textile, cosmetics, electronics and in food sectors etc. (Rawat and Kumar 2021). In comparison to other compounds, nanoparticles have more the surface area to volume ratio because of their compact size. This enhances their optical, thermal, penetrating, catalytic and various other properties which makes them much more versatile (Joudeh and Linke. 2022). In recent years, curiosity about biological surfactants has increased considerably. In contemporary discourse, there exists a burgeoning interest in biological surfactants, driven by burgeoning commercial prospects across various sectors. This momentum stems from a global shift towards products derived from natural or biological sources, amid escalating industrialization and urbanization (Rawat et al., 2020).Biosurfactants, being of biological provenance, are characterized by their non-toxic, amphipathic nature, and inherent degradability (Singh et al., 2018). Notably, they exhibit enhanced stability across a broad spectrum of conditions, including

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high temperatures, diverse pH ranges, and varying salinity levels (Rawat et al., 2024).

Biosurfactantsare secondary metabolites produced extracellularly by a wide range of microorganisms. They are amphipathic in nature, non-toxic and are self-degradable, therefore, they do not add to any environmental pollution.Because of its low cost, environmental friendliness, and less toxic nature, green NP synthesis is in high demand. Green NPs have extensive demand in various sectors such as healthcare (Joudeh and Linke 2022), defense (Dhand et al. 2015), agriculture and agrochemicals (Rawat et al. 2021) and catalysis (Vecino et al. 2021) nanotechnology is still in its infancy. Nanomaterials synthesized utilizing biosurfactants, greensynthesis processes are safe, nontoxic and environmental friendly. (Kiranet al. 2011; Płaza et al. 2014; Santhosh et al. 2022).In order to achieve sustainable development, scientists are now changing their focus to a more environment friendly method to produce nanoparticles (Rawat et al. 2020).

2. Biosurfactant

Biosurfactants are molecules that have surface actives attached that can reduce the surfaceandinterfacial tension amongtwo immiscible liquidphases (Samuelet al. 2022).Biosurfactant are produced by a wide variety of microbes likebacteria, algae,fungi, and yeasts. These biomolecules are secondary metabolites of the microbes that are produced at the stationary phase of the microbial growth during the fermentation process (Rawat et al. 2024). Owing some excellent properties biosurfactant comes in considerations for tremendous applications.

2.1. Properties of biosurfactants

Biosurfactantshave various distinctive properties, increasing their demand in contemporary industrial sectors and commercial ventures. These inherent characteristics also position them as optimal candidates for nanoparticle biosynthesis (Roy, 2014). All the important properties of the biosurfactants are discussed below in detail.

2.1.1. Surface and interface activity

Biosurfactant decreases the surface tension and interfacial pressure. Roy, 2017 reported that biosurfactantgenerated by *B. subtilis*has the potential toreduce the surface tension of water to 25 mN/m and interfacial tension of water hexadecane to less than 1 mN/m. The Critical Micelle Concentration (CMC) of biosurfactant is much smaller than that of chemical surfactants. This makes them much more versatile and useful in various fields (Yaraguppi et al. 2020).

2.1.2. Temperature and pH tolerance

One of the major features of biosurfactants is its stability in adverse conditions. Biosurfactants that are produced from extremophiles are stable and functional at extremely high pH, temperature and high salt concentrations. Elazzazy et al. (2015) reported that biosurfactants from *Virgibacillus salarius* are stable at a wide range of temperature, pH and salt concentrations. Biosurfactants produced by *Arthrobacter protophormiae* were observed to be thermally stable at the range of 30-100°C and at pH range of 2 to 12 (Roy, 2017).

2.1.3. Biodegradability

Biosurfactants are easy to degrade or self-degradable due to their biological origin, therefore, they are more compatible towards the environment. Biosurfactant not only help in biological synthesis of nanoparticles but also help in the stabilization and capping of nanoparticles. Synthetic surfactants impose ecological issues due to their non-degradable or less degradable nature. Biosurfactantsthat are produced by marine microbes were concerned for their property of biosorption of ineffectively solvent polycyclic sweetsmelling hydrocarbon, phenanthrene contaminated in aquatic surfaces (Gharaei-Fathabad 2011). Generally, biologically produced surfactants are more efficient and effective astheir Critical Micelle Concentration (CMC) is several times lesser as compared tothe synthetic surfactants, i.e., it helps in decreasing more surface tension, resulting in less application of biosurfactantsas compared to synthetic one (Desai and Banat 1997).

2.1.4. Low toxicity

Another most important property of biosurfactants that has made them a better alternative for nanoparticle synthesis is its low toxicity or non-toxic nature (Santos et al. 2016). As biosurfactants are less toxic than other compounds, they help in environmental sustainability by aiding biosynthesis of nanoparticle in an ecofriendly way. For example, the chemically derived surfactant (corexit) has greater toxicity than rhamnolipids-produced by *Photobacterium phosphoreum*, where

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corexit has ten times lower LC50 values than rhamnolipids (Porembaet al.1991).

2.1.5. Formation and breaking of emulsion

One important property of biosurfactant is their abilityto act as both emulsifier and de- emulsifier. Emulsions usually have minimal stability which can be stabilized by adding biosurfactants (Velikonja and Kosaric, 1993).Liposan produced by *Candida lipolytica,* is a water soluble emulsifier which emulsifies edible oils by encircling the droplets of oilandthusmaking stable emulsions (Cirigliano and Carman, 1985).

2.1.6. Anti-adhesive agents

Biosurfactants act like anti-adhesive agents which mean they can prevent the adhesion of microorganisms to a surface. Streptococcus thermophilus synthesizes a surfactant that hampers thegrowth of other thermophilic strains of Streptococcus on the surfaces of steel, thereby mitigating fouling. Likewise, a biosurfactant derived from Pseudomonas fluoresces impedes the adhesion of Listeria monocytogenes to steel surfaces (Gayathiri et al. 2022).

2.1.7. Emulsion forming property

The biosurfactants work as emulsifying or de-emulsifying agents (Nitschke and Costa, 2007). Emulsions are of usually two types one is oil in water (O/W) and another one is water in oil (W/O) (Akbari et al. 2018). Biosurfactants can produce micelles at concentrations above the critical micelle concentration (CMC) (Santos et al. 2016, Rangarajan, S. Majumder 2014).

2.2. Different types of Biosurfactants

Biosurfactants are diverse molecules. Their classification is based on their-molecular weights. They fall into two categories: high molecular weightbiosurfactants and low molecular weight biosurfactants. High molecular weightbiosurfactants include polymeric surfactants and particulate surfactants and Low molecular weight surfactants include glycolipids, phospholipids and lipopeptidessee Figure 1 (Shoeb et al. 2013). The details of different types of biosurfactants are as follows:

2.2.1. Glycolipids

Most of the biosurfactants are glycolipids. Glycolipids are combination of carbohydrates having long-chain aliphatic or hydroxy aliphatic acids using either ether or ester groups (Roy, 2017). Rhamnolipids, sophorolipids, and trehalolipids are the common examples of glycolipids.

Rhamnolipids, for instance, are glycolipids where one or two molecules of rhamnose are connected to one or two molecules of hydroxyl-decanoic acid (Vijaykumar and Saravanan, 2015). Burger et al. (1963) first outlined the steps for rhamnolipid production.

Sophorolipids, another type, are glycolipid biosurfactants produced by yeast. They consist of a hydrophilic sophorose unit paired with a hydroxylated fatty acid chain of either 16 or 18 carbon atoms, linked by a glycosidic bond (Oliveira et al., 2015). The fatty acids carboxylic group can exist in either free (acidic) or internally esterified (lactonic) form (Cho et al. 2022).

2.2.2. Lipopeptides and Lipoproteins

LipoproteinsandLipopeptidesform the second largest group of biosurfactants. It constitutes of lipid which is attached to a polypeptide chain. They are mainly produced by *Bacillus*, *Streptomyces* and *Pseudomonas spp.* (Henkel et al. 2019). These can be found with a linear hydrophilic head or cyclic lipopeptides known as lactone ring (Vecino et al. 2021). Surfactins is the most common example of cyclic lipopeptideshavingmany anti-bacterial, antifungal, anti-viral and even anti-inflammatory properties. Owing to these properties lipopeptide surfactins are largely used in cosmetics and pharmaceutical formulations (Vecino et al. 2021). Lichenysin is a type of surfactin which is stable at a wide range of temperature, pH and salt (Rawat et al. 2020).

2.2.3. Fatty acids, phospholipids and neutral lipids

Variousbacteria and yeast produce large amountsof fatty acids and phospholipid surfactants. In *Acinetobacter* spp. 1-N, phosphatidyl ethanolamine rich vesicles are produced. These form optically clear micro-emulsions in water and are useful in various medical applications (Vecino et al. 2021).

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2.2.4. Polymeric Biosurfactant

It includes Liposan, biodispersan, emulsan, alasan, mannoprotein and polysaccharide-protein complexes. Liposans contain 83% carbohydrate and 17% protein and are produced by *Candida lipolytica* (Santos et al. 2016). Mannoproteins are produced by *Saccharomycescerevisiae* and are made up of 44% mannose along with 17% protein.

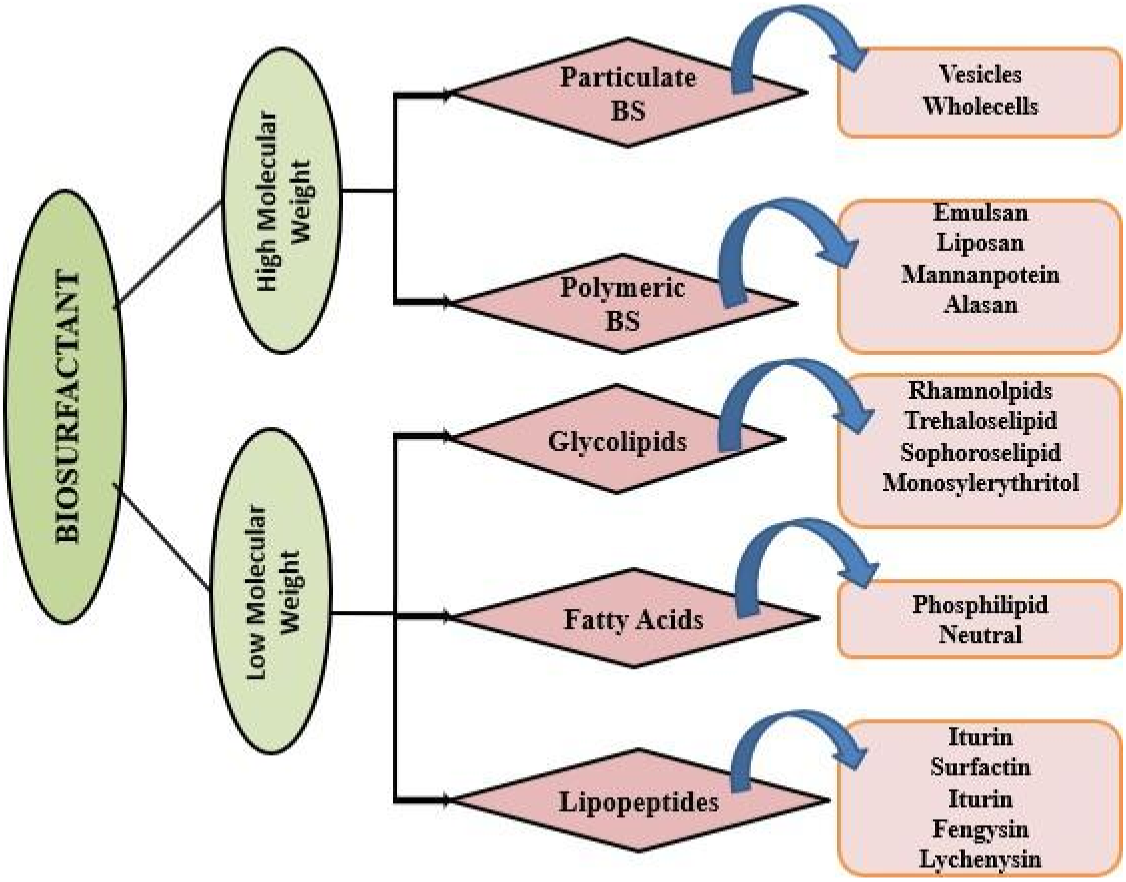

Figure 1.Different classes of biosurfactants

3. Traditional methods for nanoparticle synthesis

Nanoparticles are synthesized by two methods.Thefirst method is the top down method which includes various processes likemechanical milling, etching, laser ablation, sputtering, and electro-explosion.The second category of methods is thebottom up methods that includes chemical vapor deposition method, solvo-thermal processes and hydrothermal methods, sol–gel method, soft and hard templatingtechniques and reverses micelle methods (Ndlwana al. 2021). However, nanoparticle synthesis poses many environmental challenges as it includes the usage of many toxic compounds. This could be overcome by incorporating biological method of nanoparticle synthesis also called “green synthesis” this includes the using of biosurfactant (Plaza et al.2014).

Some other common traditional methods are like chemical reduction, sol-gel, co-precipitation, solvo-thermal synthesis, sono-chemical or electrochemical synthesis.

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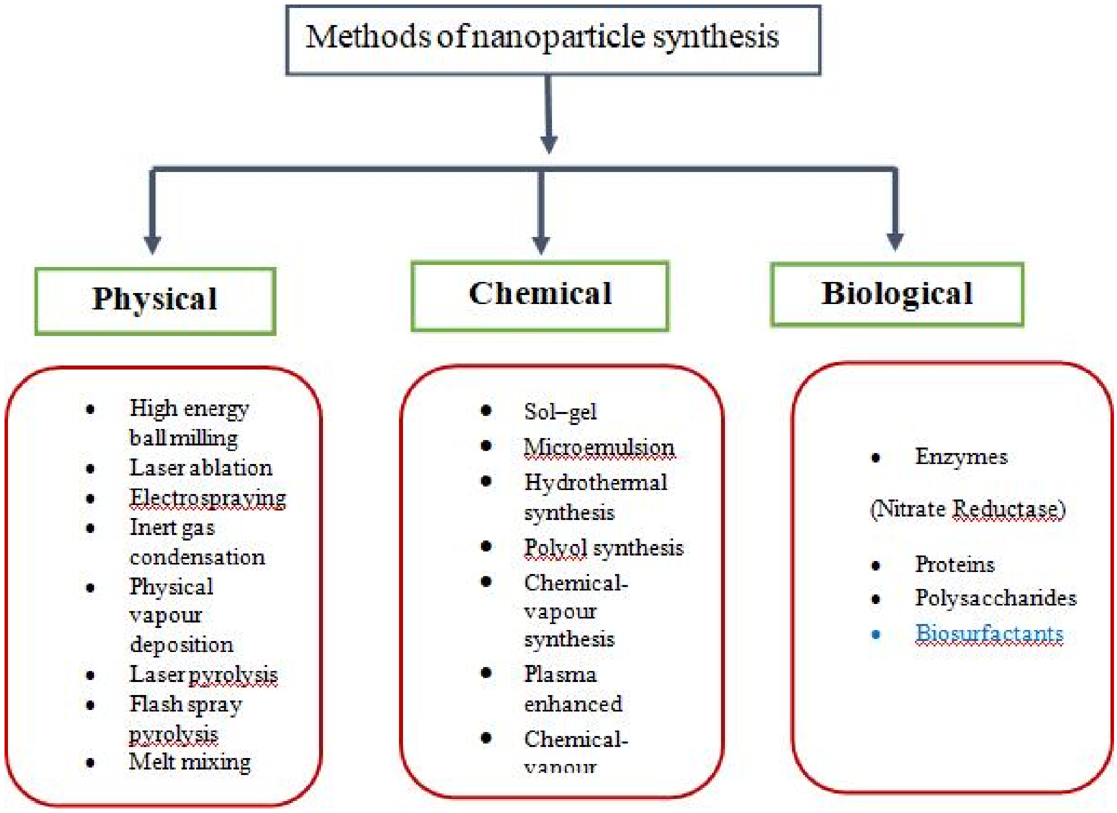

Figure 1.Illustrating the different methods for nanoparticle synthesis

4. Biosurfactant production

Biosurfactants are produced as secondary metabolites at stationary phase of the bacterial growth curve during fermentation process (Durval et al.). The bacterium was grown by introducing a 2% cell suspension (measured at 0.7 optical densities at 600 nm), into an Erlenmeyer flask containing 500 mL of a mineral salt medium supplemented with substrates like molasses, corn steep liquor and oil cakes etc. Followed by the fermentation process then biosurfactant extracted using downstream processing and characterizes those using chromatographic and spectroscopic techniques. Biosurfactant is extracellular product, therefore, after centrifugation of fermented broth it has been assumes that biosurfactant present in the supernatant (Rawat et al. 2024). The green approach for the synthesis of NPs is very cheap, safe, and inexpensive. Few green tactics for instance using phytochemicals (polyphenols, flavonoids &terpenoids), fungi, bacteria (primary and secondary metabolites), and algae have been used for the synthesis of the NPs (Shafey 2020; Mustapha et al. 2022).

5. Biosurfactant-Mediated Nanoparticle Synthesis

Surfactants are potential candidates to stabilize the nanoparticles; however, the synthetic surfactants are costly and hazardous to environment.On the other hand biourfactants are the surface active biomolecules that can be used for the NP synthesis in more sustainable way (Kiran et al. 2010).This process is not only cost-effective but can alsobe scaled up easily, as it does not require high temperature, pressure, and energy or hazardous chemicals. Biosurfactants are much more stable and non-toxic than synthetic surfactants and have been recognized as better alternative to synthetic surfactants (Rawat et al. 2020).

The principle behind this procedure involves the usage of biosurfactants as reducing and capping agents through which nanoparticles are synthesized and dispersed uniformly in the solution. The biosurfactant also gets adsorbedon the surface of nanoparticles that prevents its aggregation and promotes its stabilization also called as steric stabilization of nanoparticles (Plaza et al.2014)

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(Figure 2).In general, the green synthesis of nanoparticles includes three phases. In the initial phase, the reaction medium is obtained by the extract of plants, protein and bacterial metabolites precursor salt act as a source of metal ions (Makarov et al. 2014). In the activation phase, metal ions are chemically reducedand nucleation centers are formedwhere nanoparticlesgenerate and grow. After activation phase, comes the growth phase where adjacent smallnanoparticles spontaneously fuse into larger particles, forming aggregates. The last phase is the termination phasewhere the final shape of the nanoparticles is determined, and the compounds that participate in the reaction help in stabilizing and enhancing their properties (Álvarez-Chimal and Arenas-Alatorre 2023).

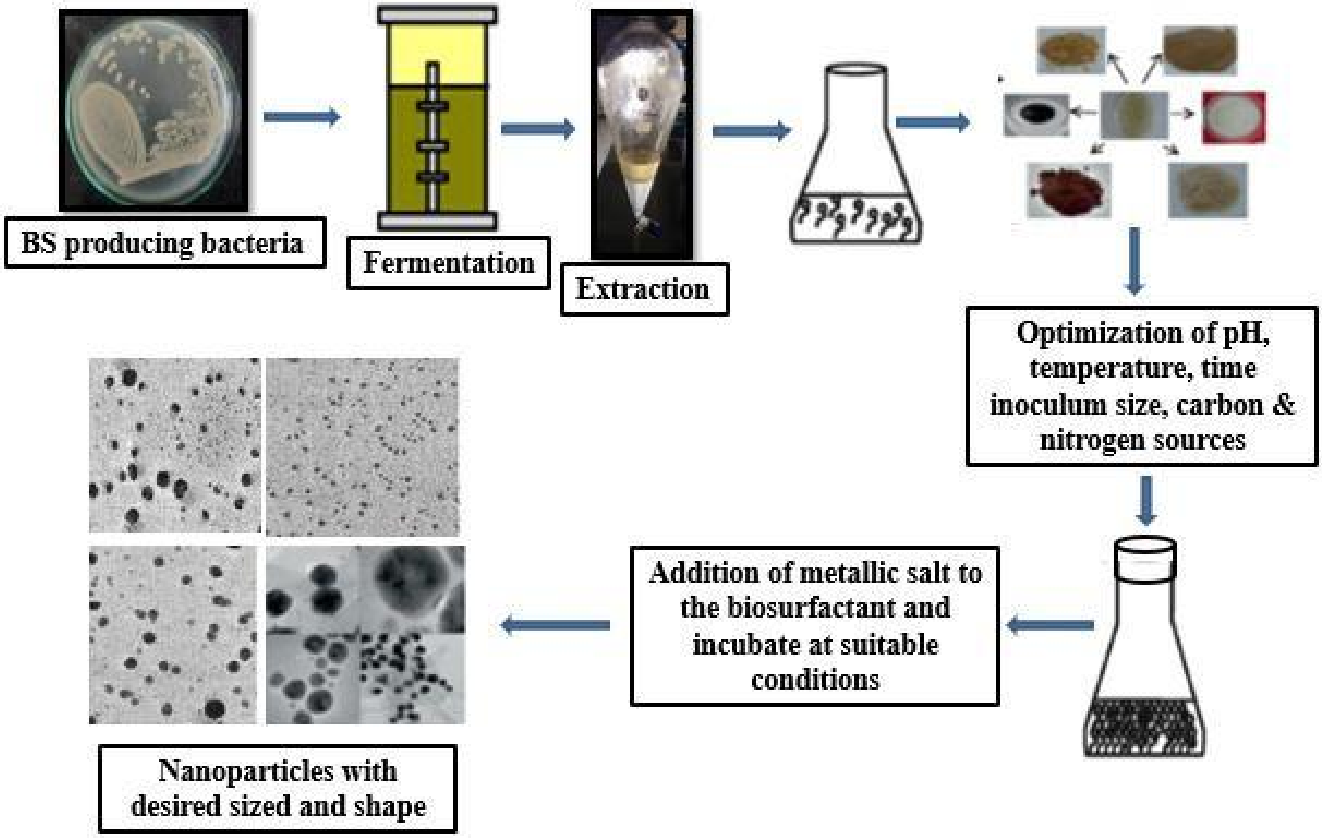

Figure 2. Schematic representation of Biosurfactant assisted nanoparticle synthesis

6. Mechanisms of action of biosurfactant in the fabrication of nanoparticle

Mechanisms of action of a biosurfactant in nanoparticle synthesis is completely depends on the surface tension reduction, interfacial tension reduction, stabilization of nanoparticles, micelle formation and functionalization of nanoparticles, each one is discussed in detailed as follows.

6.1. Surface Tension Reduction

Biosurfactants lower the surface tension of aqueous solutions, which is crucial in the initial stages of nanoparticle formation. By reducing surface tension, biosurfactant help in dispersing reactants uniformly, thus aiding in the homogeneous nucleation of nanoparticles (Rawat et al. 2022).

6.2. Interfacial Tension Reduction

In systems where nanoparticles are synthesized at the interface of two phases (e.g., oil-water emulsions), biosurfactant can reduce interfacial tension, thereby stabilizing the interface and facilitating controlled growth of nanoparticles (Vijaykumar and Saravanan 2015).

6.3. Stabilization of Nanoparticles:

Steric Stabilization: Biosurfactants can adsorb to the surface of newly formed nanoparticles, forming a protective layer around each nanoparticle. This layer provides steric hindrance, which physically prevents the nanoparticles from coming too close to each other and aggregating (Figure 3) (Carolin and Kamalesh 2024).

Electrostatic Stabilization: Many biosurfactants are ionic in nature. When they adsorb onto the surfaces of nanoparticles, they can impart a charge to the nanoparticle surface. Repulsive electrostatic forces between similarly charged nanoparticles then help prevent aggregation and coalescence, leading to a stable colloidal system (Kiran et al. 2011).

6.4. Micelle Formation

Biosurfactants can form micelles or similar aggregates in solution at certain concentrations known as the critical micelle concentration (CMC). These micelle structures can act as nano-reactors, providing a confined environment in which nanoparticles can form. The size and shape of the micelles can influence the size and morphology of the resulting nanoparticles, allowing for controlled synthesis under mild conditions (Yaraguppi et al. 2020; Rawat et al. 2022).

6.5. Functionalization of Nanoparticles:

Tailored Surface Properties: Biosurfactants can also provide functional groups (like hydroxyl, carboxyl, and amino groups) that remain on the surface of the nanoparticles after synthesis. These functional groups can be used for further chemical modifications or to enhance the interaction of nanoparticles with specific biological molecules, increasing their utility in biomedical and industrial applications (Vecino et al. 2021).

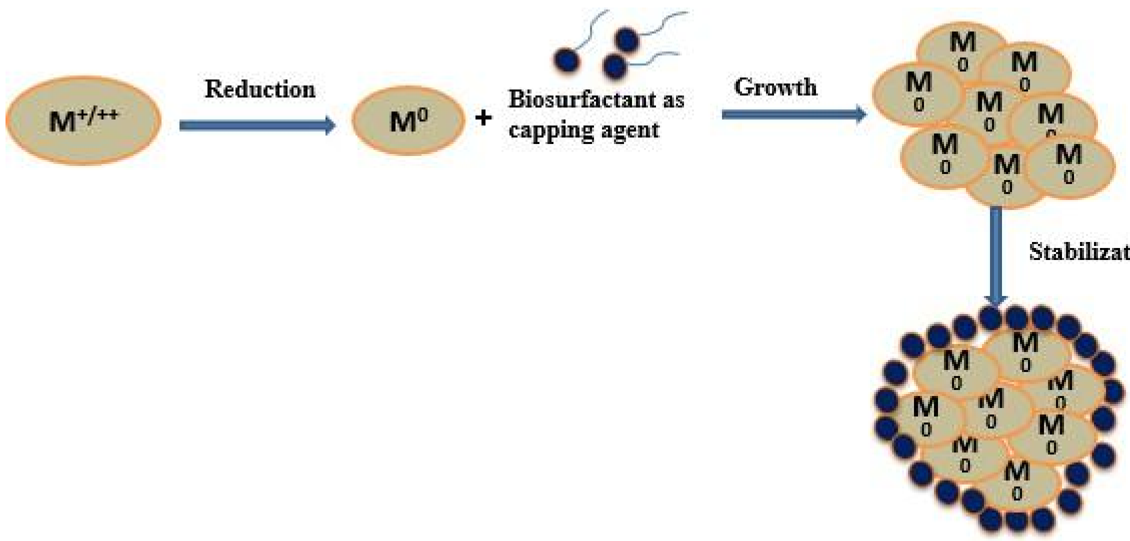

Figure 3: Demonstrate the mechanism of action of biosurfactant

7. Green synthesis of silver nanoparticles using biosurfactant

According to Kiran et al. 2010, *Brevibacter iumcasei* MSA19 was used to produce glycolipid biosurfactantunder solid state fermentation utilizing the agro-industrial waste substrate. The concentration of the purified biosurfactantwas 18 g/Lin the extract. It was found that the nano-silver particles can be synthesized inside reverse micelles using the glycolipid as stabilizer.

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The silver nanoparticlessynthesized in this study were uniform and stable for two months. Therefore, the biosurfactant-mediatednanoparticles synthesis can be considered as "green" stabilizer of nanoparticles.

They used high-quality chemicals without additional purification. First, they dissolved 1.7 grams of silver nitrate ($AgNO_3$) in 100 milliliter of pure water. They then added 0.62 grams of sodium hydroxide to this solution, causing a solid (Ag_2O) to form, which they filtered out. They dissolved this solid in 100 milliliters of a 0.4% ammonia solution to create a clear solution of silver-ammonium complex.

Next, they added 2.5 grams of a special biosurfactant drop by drop to this silver-ammonium solution and stirred gently until everything mixed evenly. Finally, they added 2 gm of glucose to this mixture and continued to stir gently.

They then exposed this mixture to UV light (with a specific wavelength and power) for 8 hours while stirring vigorously. This caused the silver complex to reduce and form tiny particles of silver stabilized by the biosurfactant. After this process, they obtained a clear liquid containing these biosurfactant-complexed silver nanoparticles, which they stored at a cold temperature (4ºC) for later use. Habibah et al. (2024) used Rhamnolipid from *Pseudomonas aeruginosa* for the production of copper nanoparticles.

Table 1: Nanoparticle (NP) synthesis employing different types of biosurfactant.

S.N.	**Types of biosurfactant**	**Reagent used**	**Action of biosurfactant**	**Type of NP**	**References**
1.	Lipopeptide	$AgNO_3$, $NaBH_4$, lipopeptide	Stabilizing agent	Ag-NP	Radha et al. 2020
2.	Lipopeptide	$AgNO_3$, $NaBH_4$ Biosurfactant	Capping and dispersing agent	Ag-NP	Rangarajan et al. 2018
3.	Lipopeptide	BS (CSL*) Mineral oil Castor oil	Co-surfactant	Nanoemulsion	Knoth et al. 2019
4.	Iturin	$AgNO_3$ Iturin	Stabilizing agent	Ag-NP	Zhao et al. 2019
5.	Surfactin	$Cd(NO_3)_2$, Na_2S Surfactin	Stabilizing agent	Cd sulphite-NP	Singh et al. 2011
6.	Surfactin	$Zn(NO_3)_2$, KOH Surfactin	Stabilizing agent	Zn-NP	Reddy et al. 2011
7.	Rhamnolipid	SDS**, Rhamnolipid, $AgNO_3$, $NaBH_4$, n-Heptane, n-butanol	Template	Ag-NP	Elakkiya et al. 2020
8.	Rhamnolipid	$ZnCl_2$, Rhamnolipid, Na_2S	Capping and stabilizing agent	Zns-NP	Hazra et al. 2013

9.	Sophorolipid	Sophorolipid, $AgNO_3$, KOH	Reducing/stabilizing agent	Ag-NP	Kasture et al. 2008
*Corn steep liquor, **sodium do-decylesulphate					

8. Factors affecting the process of Biological synthesis of nanoparticle

The process of biosynthesis of nanoparticle using biosurfactant might affect by different physiological factors such as pH, temperature, time, metal precursors, concentration of biosurfactant, types of biosurfactant.

8.1. pH

Hydrogen ion concentration (pH) is an important parameter that influences the biosurfactant mediated nanoparticle synthesis. Soni and Prakash, 2011) conducted an experiment to understand the factors affecting the silver nanoparticles (Ag NPs) synthesis by *Chrysosporium Tropicum* and *Fusarium Oxysporum.* The result showed thatthe size of nanoparticle formed increased with the decrease in *pH*. Similarly, (Palanisamy and Raichur, 2009) also concluded that the increase in pH of the solution medium reduces the size of NiO nanoparticles.

8.2. Temperature

The physical and chemical methods require high temperature whereas biological method require low temperature (<100ºC). Stavinskaya et al. (2019) have demonstrated the effect of temperature on nanoparticle synthesis. The fastest formation of nanoparticle took place at 80ºC.

8.3. Time

In green nanoparticle synthesis methods, the characteristics and types of nanoparticles produced are significantly affected by how long the reaction mixture is left to incubate. Bezzaet al. (2020) demonstrated that with the increase in reduction time, there was continuous reduction of silver metal to form AgNPs. With the increase in reaction time, the Ag NPs dissociated to form smaller particles.

8.4. Biosurfactant Concentration

Soni and Prakash, 2011,listed the effect of different concentration of biosurfactants in the production of silver nanoparticles. It has been observed that the production of silver nanoparticles increased with the increase in concentrations. Also, boosting the hydrophobic properties of surfactants increases their tendency to form micelles (Aiad et al. 2018).These factors are essential for comprehending how environmental factors affect nanoparticle synthesis because they are crucial in optimizing the production of metallic nanoparticles through biological approaches (Roy and Bharadvaja, 2019).

Table 2: Factors affecting biosurfactant mediated nanoparticle synthesis

S.N.	Factors	Effect on nanoparticle synthesis	References
1.	pH	pH plays a crucial role in biosurfactant-mediated nanoparticle synthesis as it influences the stability and activity of the biosurfactant, thus affecting nanoparticle formation.	Palanisamy and Raichur, 2009
2.	Temperature	The temperature of the reaction affects the rate of biosurfactant production by microorganisms and subsequently influences nanoparticle synthesis Reduction faster between 60ºC to 100ºC	Stavinskaya et al. 2019
3.	Metal precursor	Different metal precursors have varying reactivities with biosurfactants, leading to differences in nanoparticle size, shape, and composition.	Rawat et al. 2022

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4.	Time	Depends on time required to reduce the metal	Darroudi et al. 2011
5.	Biosurfactant concentration	The concentration of biosurfactant in the reaction mixture affects the size, morphology, and stability of nanoparticles.	Soni and Prakash, 2011
6.	Biosurfactant type	Different types of biosurfactants, such as glycolipids, lipopeptides, and rhamnolipids, have varying effects on nanoparticle synthesis.	Rawat et al. 2022

9. Characterization ofBiosurfactant-Mediated Nanoparticles

Nanoparticles characterization is done to understand both physical and chemical properties of nanoparticles. The physical properties include size, shape, crystal structure, etc. whereas chemical properties include bonding of ligands or other molecules (Greenwood and Michael, 2018).

9.1. *X-ray* diffraction (XRD)

To study the crystalline structure or to determine the nature of the phase, lattice parameters and crystalline grain size XRD can be used , (Mourdikoudis et al. 2018).The Scherrer equation can be used in X-ray diffraction to determine the average size of crystalline structure (Holder et al. 2019).

9.2. Scanning Electron Microscopy (SEM)

SEM is used to determine the physical properties of nanoparticles (VladárandHodoroaba, 2020).By scanning the surface with the electron beam and detecting the signals generated, SEM generates images and data that can be used to characterize the sample at the micro and nano scales (Akhtaret al.2018).

9.3. UV-Visible Spectroscopy

UV-visible absorbance spectroscopy examines how materials absorb light at different wavelengths. It covers wavelengths from the near ultraviolet region at around 200 nm to the visible spectrum, spanning from violet at 380 nm to red at 740 nm. Using a UV-visible spectrophotometer, this technique analyzes absorbance across a range of 200 to 900 nm, providing insights into the material's properties based on its interaction with light (Deshmukh et al 2022).Paramelle et al. (2014) used UV-Visible Spectroscopy to quickly estimate the concentration and size of modified and mono-dispersed silver nanoparticles from their optical spectra.

9.4. Transmission Electron Microscopy(TEM)

TEM works by transmitting a beam of electrons through a thin specimen, which interacts with the nanoparticles to produce an image. (Smith, 2015)**.**Transmission electron microscopy is a powerful tool to study the interaction of the nanoparticles with subcellular structures (Malatesta2021).

9.5. Fourier Transform Infrared (FTIR)

FTIR is used to analyze biomolecules by detecting changes in their composition based on variations in functional groups. It works by measuring the vibrations and rotations of molecules induced by infrared radiation at specific wavelengths (Rawat et al. 2024). By doing so, FTIR can identify structural differences in molecular bonds between different entities, providing insights into their interactions. There are several popular methods within FTIR spectroscopy for characterization, including (Eid, 2022).To determine the dimensions of a particle and the degree of homogeneity between various particles in a colloid,techniques like DLS, Zeta potential etc can be used (Greenwood,2018).

10. Applications of biosurfactant mediated nanoparticles

Nanoparticles are used in various sectors such as health care sectors, food and pharmaceutical industries, cosmetic industries and environment cleanup sector.

Nanoparticles synthesized using biosurfactants have shown versatile applications not only in biomedicine serving as effective agents against bacteria, fungi, biofilms, cancer cells, and in wound healing but also acting as drug delivery agent. Nanoparticles are playing a vital role in imaging process like X-ray, MRI & CT scan image for the more accuracy. Nanoparticles could be used in bioremediation of pollutants such as chlorinated solvents, oil spills, particulate matters, organic compounds etc. fromthe soil and the groundwater (Vaseashta et al 2007). Nanoparticles

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composed of various metals and their oxidative derivatives, can be used in most of theorganic reactionslikeepoxidation, reductive coupling reactions, hydrogenation, alcohol oxidation etc. (Carolin and Kamalesh 2024). Nanoparticles represent a promising platform for advancing cancer treatment by overcoming many of the limitations associated with conventional therapies (Gavas et al. 2021).

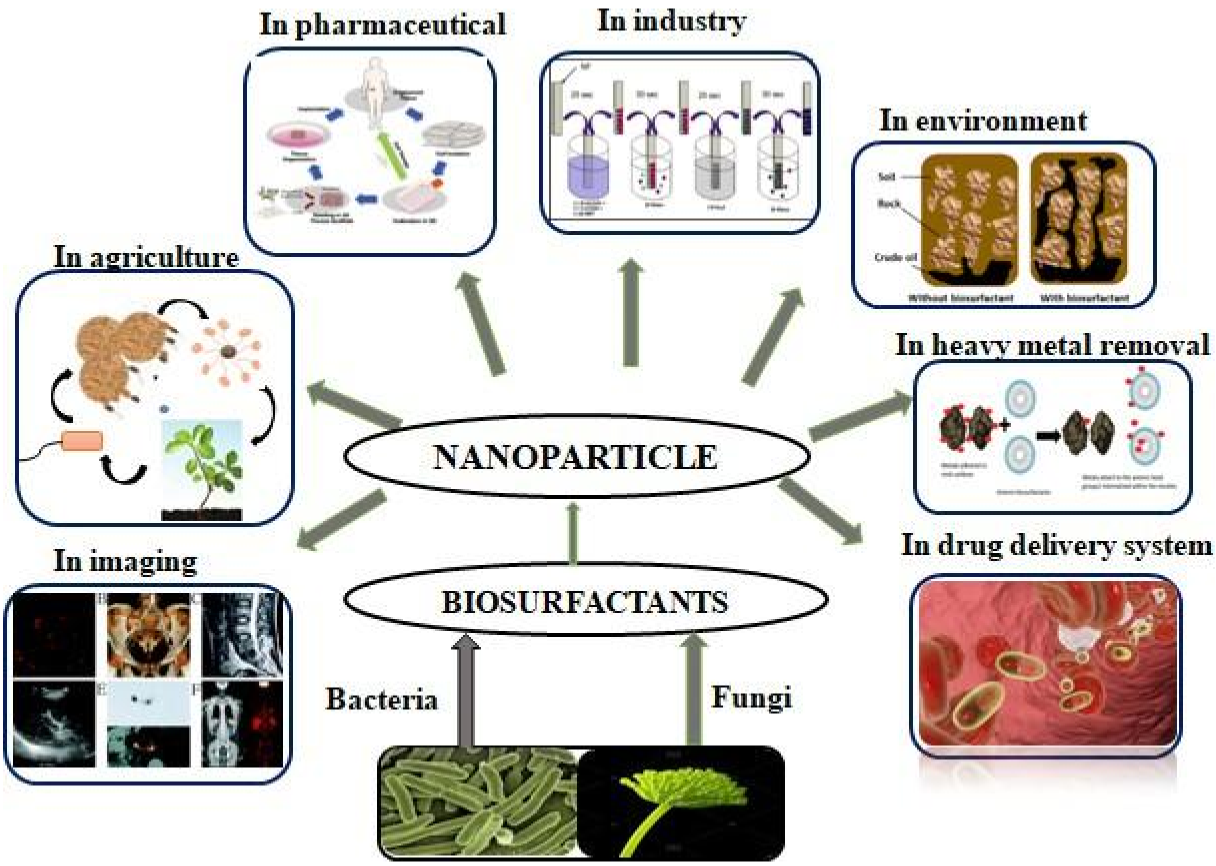

Figure 4: Illustrates the application of nano-particles synthesized bybiosurfactant

11. Conclusion

Biosurfactantsdisplay multifaceted roles in the synthesis of nanomaterials. They not only reduce the surface area and the interfacial tensions that aid in the nucleation and growth of nanoparticles but also provide stabilizing forces that prevent aggregation, control particle size and morphology, and contribute to the environmental sustainability of the synthesis process. Their natural origin and biocompatibility further underscore their potential in advancing green nanotechnology.The utilization of biosurfactants for nanoparticle synthesis offers a promising avenue for sustainable technological advancements with broad applications. The unique properties of biosurfactant such as amphipathic nature, stability under extreme conditions, low toxicity, and biodegradability, make them ideal candidates for nanoparticle synthesis. By harnessing the power of microorganisms, biosurfactant-mediated synthesis provides a green and eco-friendly alternative to traditional methods, minimizing environmental impact and health hazards associated with toxic compounds.Moreover, the versatility of biosurfactant-mediated nanoparticles is evident in their applications across various fields. From biomedicine to environmental remediation and catalysis, these nanoparticles exhibit remarkable efficacy and safety profiles. Additionally, their potential in advancing cancer treatment, medical imaging, and drug delivery underscores their significance in modern healthcare and

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diagnostics.As research in this area continues to evolve, further exploration of biosurfactant-mediated nanoparticle synthesis holds promise for addressing global challenges in healthcare, environmental sustainability, and industrial processes. By optimizing synthesis conditions, characterizing nanoparticle properties, and exploring novel applications, biosurfactant-mediated nanoparticles are poised to drive innovation and contribute to a more sustainable future.

Conflict of interest: The authors have declared no conflict of interest.

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