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Review article

Advances in stabilization of metallic nanoparticle with biosurfactants- a review on current trends

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ABSTRACT

Recently, research based on new biomaterials for stabilizing metallic nanoparticles has increased due to their greater environmental friendliness and lower health risk. Their stability is often a critical factor influencing their performance and shelf life. Nowadays, the use of biosurfactants is gaining interest due to their sustainable advantages. Biosurfactants are used for various commercial and industrial applications such as food processing, therapeutic applications, agriculture, etc. Biosurfactants create stable coatings surrounding nanoparticles to stop agglomeration and provide long-term stability. The present review study describes a collection of important scientific works on stabilization and capping of metallic nanoparticles as biosurfactants. This review also provides a comprehensive overview of the intrinsic properties and environmental aspects of metal nanoparticles coated with biosurfactants. In addition, future methods and potential solutions for biosurfactant-mediated stabilization in nanoparticle synthesis are also highlighted. The objective of this study is to ensure that the stabilized nanoparticles exhibit biocompatible properties, making them suitable for applications in medicine and biotechnology.

1. Introduction

Nanotechnology is a technological science that uses materials and special instruments to change the properties of materials at the molecular level. It is the study of matter at the macromolecular level with a range of a hundred nanometers. The development of such materials has the advantage of regulating or modifying matter at the molecular level and exhibiting novel and special properties [1,2]. By integrating applications of nanomaterials and information technology into current biological concerns, nanobiotechnology can improve various approaches in the life sciences. The novel properties and uses of materials at the nanoscale are investigated in the cutting-edge domains of nanoparticles and nanotechnology. Nanotechnology makes use of the unique features that nanoparticles—which usually have sizes between 1 and 100 nm—have over bulk materials to create a variety of novel applications [3]. Nanotechnology research has evolved from drug delivery and molecular diagnostic approaches to a rapidly expanding field with diverse applications. This breakthrough method has become a cornerstone of the future of nanotechnology and holds the key to an environmentally sustainable civilization in the twenty-first century.

Nanotechnology is useful for disease detection, diagnostic imaging, tissue engineering, drug distribution, and disease treatment [4]. Green nanotechnology must be harnessed to develop improved processes and strategies to increase the efficacy of readily available drugs and antimicrobial chemicals. With its novel properties, nanotechnology opens a wide range of opportunities for advancement in

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various industries [5]. Surface effects predominate at the nanoscale, increasing surface energy. By aggregating, nanoparticles often reduce this energy and cause instability. Stabilization involves preventing or minimizing agglomeration and maintaining the dispersed state of nanoparticles [6]. Adding polymer chains to encase nanoparticles in a barrier that prevents them from aggregating. pH of the solution can be changed to affect nanoparticle surface charge and create electrostatic stabilization. Limiting air and moisture exposure to stop unintended reactions on the surface of the nanoparticles. Amphiphilic substances, containing both hydrophobic and hydrophilic areas, are known as surfactants. By enclosing nanoparticles in a protective coating and minimizing inter-particle interactions, surfactants can stabilize them. Surfactants provide a barrier that stops agglomeration by adhering to the surface of the nanoparticles. Depending on their charge, they can be categorised as zwitterionic, nonionic, or ionic (anionic, cationic). The problems caused by the instability of nanoparticles can be effectively and sustainably solved by biosurfactants. Their distinct characteristics, biocompatibility, and favourable effects on the environment provide them appealing options for augmenting the stability and functionality of nanoparticles in diverse industrial, medicinal, and environmental uses. Biosurfactants have the potential to significantly contribute to the responsible and sustainable application of nanotechnology as this field of study develops.

1.1. *Nanoparticle*

Nowadays, the use of nanoparticles has enriched the field of therapeutic applications [7]. Although there are different ways to categorize nanomaterials, those commonly used by the scientific community are based on their properties, behavior, and potential applications ents: carbon-based, dendrimer-based, magnetic, metal-based, etc. [8]. Nanomaterials are also considered very important in fields such as optoelectronics, environmental pollution, drug delivery, communication systems, pharmaceuticals, etc [9]. The design of nanoparticles (NP) includes organic molecules, inorganic molecules or mixed forms of these compounds [10]. Inorganic forms of the raw materials (NPs) include gold, copper, iron, nickel, and silver nanoparticles [11]. The cytotoxic effect of NPs is widely used in areas such as food storage, textiles, healthcare, environmental sensing, and medical device coating. Materials, components, devices, and algorithms developed using nanotechnology range in size from 1 to 100 nm [12]. The exceptionally large surface-to-volume ratio and spontaneous reactivity are two different physicochemical properties of the developed NPs that distinguish them from the corresponding bulk materials. Numerous applications in the fields of medicine, telecommunications, power generation, and bioremediation take advantage of these novel physicochemical properties of NPs. As a result, most researchers focused on producing nanoparticles in an environmentally friendly manner [13]. With their advantageous and improved properties in terms of their structure and shape, new uses for NP in science and technology are emerging.

1.2. *Metallic nanoparticle*

Metallic nanoparticles (MNPs) have different properties and morphologies and a wide range of potential applications. Nowadays, many nanomaterials focus on transition metals due to their numerous remarkable properties such as large surface area, low melting pressure and temperature, excellent tensile strength and good optical properties [14]. MNPs are widely used in a variety of fields, such as oil and gas industry, semiconductors, lasers, ceramics, coatings and paints, catalysts, medical products, skin care products, and others [15], as shown in Fig. 1. Compared to metallic materials or metallic ions, metallic nanoparticles have been the subject of extensive research in recent years. The various types of MNP include iron, zinc, copper, nickel, silver, gold, etc. Table 1 shows the applications of various metallic nanoparticles as explained in different studies. Depending on the amount of metals used in their preparation, metallic nanoparticles are classified as monometallic, bimetallic, or trimetallic. MMN or monometallic nanoparticles are synthesized by reduction of a single metal solution using reducing and stabilizing chemicals [16]. Monometallic nanoparticles consist of a single type of metal, such as gold (AuNPs), silver (AgNPs), or copper (CuNPs). These nanoparticles exhibit unique properties attributed to the specific metal employed. BMN or bimetallic nanoparticles exhibit exceptional biological properties due to their

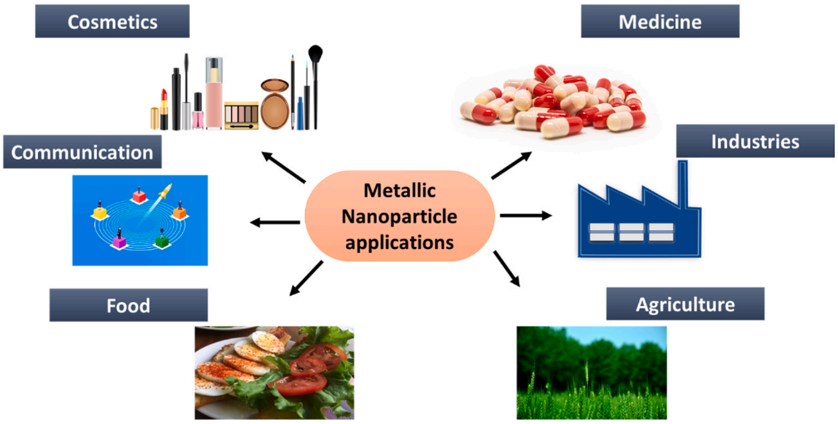

Fig. 1. Potential applications of metallic nanoparticles.

Table 1
Studies on the different sizes and shapes of metallic nanoparticles and their applications.

Type of metallic nanoparticle	Shape	Size	Applications	References
Copper nanoparticles	Spherical	30 nm	Antibacterial against and anti-biofilm activities	[19]
		10–16 nm	Antibacterial activity	[20]
		20 nm	Optoelectronic applications	[21]
Copper oxide nanoparticles	Agglomerated spherical shaped Particles	20–35 nm	Antibacterial activity	[22]
	Spherical crystalline particles	48 nm	Active against urinary tract pathogen	[23]
Gold nanoparticles	Crystalline spherical particles	60 nm	Active against fungal strains	[24]
		3–37 nm	Antibacterial activity	[25]
	Hexagonal	36 nm	Catalytic activity	[26]
	Spherical	60 nm	Antifungal activity	[27]
		54 nm	Cytotoxicity	[28]
	Cubic face centered	15 nm	Nonlinear optical applications	[29]
Iron nanoparticles	Spherical amorphous Particles	2.6–6.2 nm	Effective against *E. coli*	[30]
	Spherical crystalline particles	11 nm	Activity towards *E. coli* and *Staphylococcus aureus*	[31]
Zinc oxide	Spherical	129 nm	Antibacterial and anti-biofilm activity	[32]
		35 nm	Antibacterial and antioxidant applications	[33]
Silver nanoparticles	Spherical crystalline particles	6–26 nm	Inhibited mycotoxin production	[34]
		13 nm	Active against human pathogens	[35]
	Spherical	12–26 nm	Antibacterial, catalytic and antioxidant activity	[36]
		15–87 nm	Larvicidal and pupicidal toxicity	[37]
		20–40 nm	Antibacterial activity	[38]
	Spherical and rod	26 nm	Antibacterial, catalytic and Antioxidant	[39]
	Triangle, pentagonal and hexagonal	122–164 nm	Antifungal activity	[40]
Lead	Spherical	38 nm	Dye degradation	[41]
		2.3–7.5 nm	Catalytic activity and antibacterial Activities	[42]

chemical properties, which are attributed to the complementary activities of the two metals [17]. Bimetallic nanoparticles, on the other hand, involve the combination of two different metals, leading to synergistic effects that can enhance catalytic activity, structural stability, and electronic properties. Examples include palladium-gold nanoparticles (Pd-AuNPs) and silver-platinum nanoparticles (Ag-PtNPs). TMN or trimetallic nanoparticles possess effective antibacterial capacity and have been shown to be superior to bimetallic and monometallic nanoparticles [18]. Trimetallic nanoparticles, incorporating three different metals, offer even greater compositional diversity and can display intricate functionalities. Their unique combination of metals, like gold-silver-palladium nanoparticles (Au–Ag-PdNPs), allows for fine-tuning of properties, making them valuable in various applications ranging from catalysis to biomedical research. Due to the use of nanomaterials in commercial applications, the types of metallic nanoparticles described in this review are produced in large quantities for various purposes.

1.3. Semi-metal nanoparticle

Semimetals, also known as metalloids, are elements that possess properties intermediate between metals and nonmetals. Because of their special physical, chemical, and electrical characteristics, semi-metal nanoparticles—also referred to as metalloid nanoparticles—occupy an interesting niche in nanoscience. Silicon (Si) nanoparticles are among the most well-known types of semi-metal nanoparticles. In bulk silicon, it is usually regarded as a metalloid, but at the nanoscale, it exhibits certain intriguing characteristics. Size-dependent optical, electrical, and catalytic capabilities of silicon nanoparticles make them attractive options for a range of uses, including solar cells, sensors, and medicinal devices [43]. Germanium (Ge) is another important semi-metal nanoparticle. Similar to silicon, germanium has distinct nanoscale characteristics and behaves as a metalloid. Germanium nanoparticles' configurable bandgap and compatibility with current silicon-based technologies have drawn attention to their potential in optoelectronic devices, photovoltaics, and biological applications [44].

1.4. Metal oxide nanoparticle

Due to their special characteristics, which include a large surface area, variable chemical reactivity, and improved physical and optical qualities over their bulk counterparts, metal oxide nanoparticles have attracted a lot of interest in a variety of sectors. Applications for these nanoparticles include remediation of the environment, biomedical engineering, sensing, energy storage, and catalysis. Titanium dioxide is a well-known example of a metal oxide nanoparticle (TiO_2). Because of their superior photocatalytic activity, TiO_2 nanoparticles are frequently utilised in water purification, environmental remediation, and self-cleaning surfaces. Because of their optical and electrical characteristics, TiO_2 nanoparticles are also used in solar cells, sensors, and photovoltaic devices [45].

1.5. Production of metallic nanoparticle

Two-step processes are used in the chemical generation of metallic nanoparticles: In the first step, a reducing agent is used for the reduction process and in the second step, a stabilizing agent is used to smooth the generated nanoparticles [46]. The top-down technique and the bottom-up approach are the two main methods used in the fabrication of nanomaterials [47]. Chemical vapor deposition, sol-gel method, self-assembly and biological synthesis are the examples of bottom-down approaches [48]. Lithography, ball milling and chemical etching are the examples of top-down approaches [49]. Using living organisms, such as bacteria or plants, to synthesize nanomaterials. This eco-friendly approach is known as biological synthesis. Nanomaterials consist of metals, polymers, and other materials that can be derived from biological and non-biological resources [50]]. Moreover, these materials have an impact on their specificity and compounds. Metallic nanoparticles are synthesized using expensive physical and chemical methods that usually release harmful byproducts into the environment [51]. The physical methods used for the synthesis of metallic nanoparticles include thermal decomposition, irradiation, electrolysis and so on. In the physical method, a complex and expensive filtration technology is used to produce the metallic nanoparticles. In the chemical method, sodium borohydride and sodium citrate are used to synthesize the metallic nanoparticles. However, these chemicals pose a health risk to humans and the environment [52]. For example, the use of formaldehyde to synthesize nanoparticles is risky to both human cells and the environment. In certain cases, improper use of these methods can reduce the solubility of NPs. In order to evaluate the stability of nanoparticles to remain dispersed in solution without aggregation or sedimentation, the techniques like zeta potential measurement and turbidity analysis are employed to assess colloidal stability. Studies have revealed that polymeric coatings, like polyethylene glycol (PEG), play a vital role in improving the stability of nanoparticles in biological environments by preventing protein adsorption and opsonization [53]. Crosslinking agents such as glutaraldehyde enhance stability by forming covalent bonds between nanoparticle surfaces, making them more resistant to changes in environmental conditions [54].

2. Biosurfactant

The number of research studies on biosurfactants has increased exponentially in the last decade [55]. The growing interest in biosurfactants is fueled by the increasing interest of industry in environmentally friendly processes and product use. Biosurfactants, also referred to as biologically active chemicals, natural surfactants, and renewable surfactants which are generally produced by plants and microorganisms [56,57] and have been effectively used in various applications [58,59]. There are a variety of microorganisms such as bacteria, yeasts, and filamentous fungi used to generate biosurfactants that lead to different properties and structures [60]. Microbially derived biosurfactants are effective substitutes for chemical surfactants [61]. In addition to terrestrial habitats, freshwater

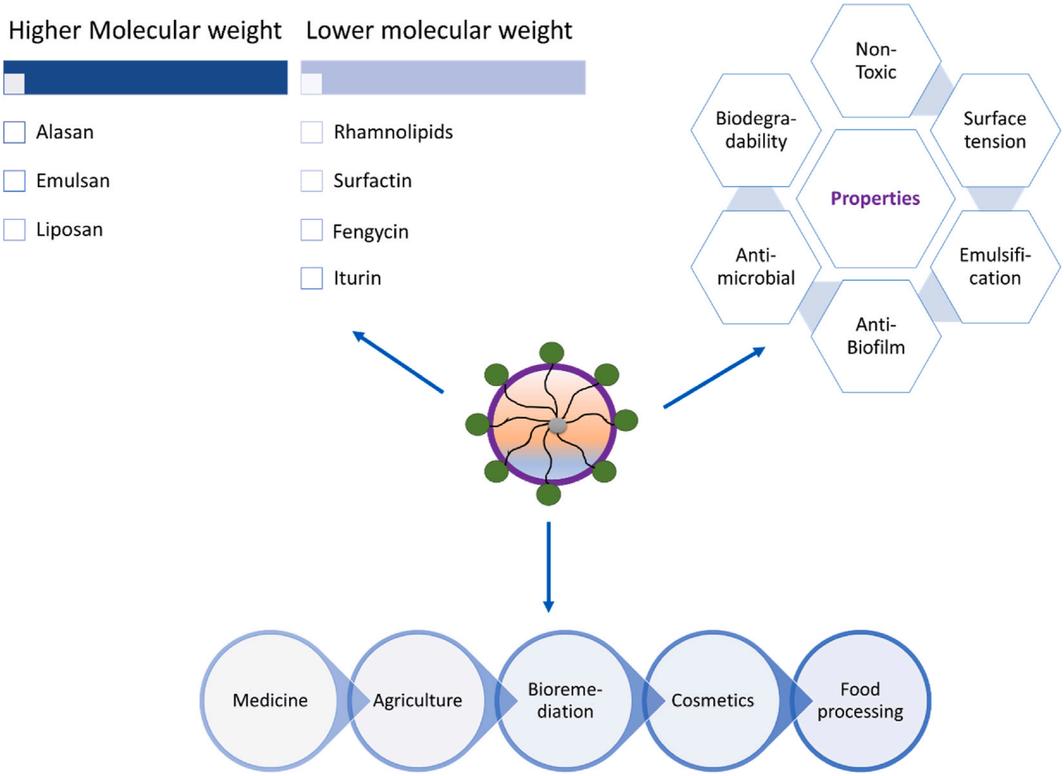

Fig. 2. Schematic representation of the types of biosurfactants, their properties and uses.

and coastal ecosystems have also been reported to contain microbial biosurfactants [62]. Surfactants are amphiphilic molecules used to solubilize and mobilize contaminants in liquid solutions, allowing bacteria to recover and reuse them [63]. Due to their ionic character, non-toxicity, high emulsifying ability, interfacial properties and environmental compatibility, biosurfactants are considered attractive alternatives for various applications [58]. Because they are biodegradable and frequently sourced from natural sources, biosurfactants help stabilize nanoparticles in ways that are less harmful to the environment. Sustainability is encouraged by the fact that many biosurfactants may be made from renewable resources, which lessens reliance on non-renewable raw materials. The hydrophilic part of the biosurfactant is composed of esters, hydroxyl, phosphate and carboxyl groups. The hydrophobic part of the biosurfactant is composed of fatty acids, fatty alcohols, etc. The increasing interest in biosurfactants is due to their numerous practical applications in recent decades because they have unique properties that are used in a variety of industries [64–66], as shown in Fig. 2.

2.1. Biosurfactant types and characteristics

2.1.1. Types

Depending on the molecular weight, two main categories are distinguished: low molecular weight biosurfactants and high molecular weight biosurfactants [67]. Table 2 describes the literature studies on the different classifications of biosurfactants and their properties. Fig. 2 shows the classification of low molecular weight and high molecular weight biosurfactants.

2.1.1.1. Low molecular weight biosurfactants. Biosurfactants, whose molecular weight ranges from 500 to 1000 kDa, are low molecular weight biosurfactants and are composed of fatty acids, glycolipids, lipopeptides and phospholipids. Since they are considered the best technique for reducing interfacial and surface tension, they can be used effectively due to their low molecular weight [92]. The glycolipids have a polysaccharide at their head groups, which is affected by the pH of the electrolyte and leads to changes in micelle formation. The rhamnolipids consist of one or two rhamnose molecules and three fatty acid molecules, which have a chain length of 8–22 carbon atoms. The first OH group forms a glycosidic bond with the reducing side of rhamnose carbohydrates, while the hydroxyl group of the second acid contributes to the synthesis of esters [56]. Sophorolipids contain a sophorose, a disaccharide glucose molecule that can form the hydrophilic head and the hydrophobic part and consists of 16–18 carbon atoms [56]. Surfactin is a circular lipopeptide biosurfactant in which the peptide moiety is formed by the multienzyme peptide synthase complex.

2.1.1.2. High molecular weight biosurfactants. These biosurfactants have high molecular weights in the range of >1000 kDa and include particulate and polymeric surfactants. Due to their strong emulsifying effect, they are widely used as stabilizers and emulsifiers in industrial applications. Excellent examples of high molecular weight biosurfactants are alasan and emulsan [55,93]. These biosurfactants exhibit different structural and functional variants and are crucial for the solubilization of hydrophobic substances. The HMW (polymeric) biosurfactant emulsan consists of an anionic lipopolysaccharide and a protein. Alasan is a compound consisting of an anionic heteropolysaccharide containing alanine.

2.1.1.3. Cationic and anionic biosurfactants. Cationic and non-ionic surfactants have demonstrated remarkable effectiveness in this

Table 2
Different properties of biosurfactants in different research studies.

Characteristics	Types of biosurfactant	Results	References
Surface tension	Lipopeptide	25.9 mNm^{-1}	[68]
		38 mNm^{-1}	[69]
	Rhamnolipid	25.19 mNm^{-1}	[70]
		38.33 mNm^{-1}	[71]
	Sophorolipid	42 mNm^{-1}	[72]
	Glycolipid	31 mNm^{-1}	[73]
Emulsification activity	Lipopeptide	57 %	[74]
		95.4 %	[75]
		87 %	[76]
	Rhamnolipid	69.69 %	[70]
Critical micelle concentration	Glycolipid	50 mgL^{1}	[77]
		40 mgL^{1}	[78]
	Lipopeptide	80 mgL^{1}	[79]
	Sophorolipid	50 mgL^{1}	[80]
	Rhamnolipid	100 mgL^{1}	[81]
Anti-biofilm activity	Rhamnolipid	83 %	[82]
		88 %	[83]
		70 %	[84]
		99 %	[85]
	Lipopeptide	70.3 %	[86]
Anti-microbial activity	Lipopeptide	23.0 ± 1.6 mm	[87]
		13 ± 0.5 mm	[88]
	Lichenysin	12.6 mm	[89]
	Rhamnolipid	254.89 ± 6.42 nm	[90]
	Glycolipid	25 mm	[91]

regard. Cationic surfactants, characterized by their positively charged hydrophilic head groups, exhibit strong electrostatic interactions with negatively charged metal nanoparticles, aiding in their stabilization [94]. Examples include cetyltrimethylammonium bromide (CTAB) and cetylpyridinium chloride (CPC), which have been widely employed for stabilizing metal nanoparticles in diverse systems [95]. On the other hand, non-ionic surfactants, such as polyvinyl alcohol (PVA) and polyethylene glycol (PEG), offer stability through steric hindrance and hydrogen bonding, making them suitable candidates for metal nanoparticle stabilization [96]. The versatility of cationic and non-ionic surfactants in metal nanoparticle stabilization underscores their significance in advancing nanotechnology and materials science.

2.1.2. Characteristics of biosurfactants

Based on the properties of biosurfactants such as surface tension, emulsifying activity, micelle formation, anti-biofilm activity and antimicrobial activity, the application of biosurfactants varies as shown in Fig. 2.

2.1.2.1. Surface tension reduction. Biosurfactants can effectively reduce surface tension and interfacial activity between two surfaces, liquid or solid. Biosurfactants are believed to be far more efficient than chemical surfactants because they can lower surface tension even at low concentrations [97,98]. The concentration of the surfactant at the surface is initially the same as in the total solution, but as it adsorbs to the surface of the solution, the surface tension decreases, resulting in an equilibrium surface tension. Microorganisms producing surfactants in marine sponges can decrease the surface activity from 69 to 30 mN m^{-1} [99]. The time required for transfer and sorption at the surface can range from milliseconds to days, depending on the concentration and structure of the surfactant. The surfactant concentration is negatively related to the adsorption rate [100]. Surface tension must be reduced to create kinetically stable emulsifiers. Biosurfactants are able to adsorb on surfaces due to the combination of their hydrophobic and hydrophilic properties.

2.1.2.2. Emulsifying activity. Emulsification is a stable non-equilibrium process that produces bubbles called emulsions. An emulsification is a heterogeneous process consisting of immiscible liquids dispersed as tiny droplets in another liquid. In the agricultural, cosmetic, and pharmaceutical industries, biosurfactants are commonly used in emulsification processes [101]. The emulsifying activity of the biosurfactant depends on the substrate used for the application. They are often used as an adjunct to promote bioremediation and to remove oil contamination in the environment [102]. An emulsifier made from Quillaja saponin extract is commercially available for use in food applications. Usually, this substance is offered either in powder form or as a solution mixed with water [103].

2.1.2.3. Critical micelle concentration (CMC). The maximum reduction in surface activity can be achieved at this surfactant concentration, which also promotes the formation of micelles [104]. The wettability and dynamic properties of the surfactant are affected by the formation of micelles, which can take the form of round, rod, disc, or other more complex shapes, as the surfactant molecules cluster in the bulk phase above the CMC during the micellization process. The equilibrium mechanism of micelle formation leads to the formation of a nanostructure. When surfactants are present in increasing concentrations in aqueous solutions, they often mix and form micelles. The development of micelles can be influenced by varying the temperature and concentration of biosurfactants. The repulsion pressure between the head groups limits the number of micelle compounds. As a result, increasing the surfactant concentration above the CMC results in more total micelles rather than larger micelles.

2.1.2.4. Anti-biofilm activity. Bacterial cells clump together to form biofilms covered by a self-produced external polysaccharide matrix. The existence of biofilms raises several issues in medicine that complicate the clinical management of chronic infections. The use of synthetic drugs and chemicals can be reduced by preventing the formation of pathogenic biofilms on medical materials through the adsorption of biosurfactants [103]. The potential of biosurfactants as an alternative to control biofilms has been extensively researched [91]. The wettability and amphipathic properties of biosurfactants allow them to directly affect corrosion activities by altering the adhesion and deadhesion of microorganisms. According to Coronel-Leon et al. [105], biosurfactants such as lichenysin produced by *Bacillus licheniformis* showed an anti-biofilm effect both before and after biofilm treatments. Araujo et al. [81] demonstrated that rhamnolipids have an anti-adhesive and antibiofilm effect against Gram-positive and -negative bacteria by inhibiting the formation of biofilms on the surfaces of polystyrene and stainless steel.

2.1.2.5. Antimicrobial property. There are numerous reports of biosurfactants with antimicrobial properties, including surfactin, iturin, rhamnolipids, and fengysin [106–108], used in biotechnological and medical applications. Biosurfactants exhibit antibacterial properties against bacteria by destroying their membranes and causing them to die [109]. Unlike conventional antibiotics, the antibacterial properties of biosurfactants use alternative processes to kill the target organisms. Cornea et al. [110] presented the development of cell-mediated antimicrobial biosurfactants from different *Lactobacillus* strains. Due to the inherent properties of biosurfactants, scientific interest in antimicrobial activity is rapidly increasing.

2.2. Biosurfactant role in stabilization

For the production of nanoparticles, it is currently necessary to identify non-toxic technologies. The use of biosurfactants as coupling agents is one of the recent methods for sustainable, environmentally friendly and compatible synthesis of bioactive metallic nanoparticles [111]. In addition to their use in industry, surfactants represent an important opportunity to overcome the current limitations of nanotechnology. Microemulsions or inverted micelles have been successfully used in several research projects to generate size- and morphology-based NP [112]. The properties of inverted micelles include extremely low interfacial tension and large surface areas, which can be used as nanoreactors to generate nanoparticles with narrow size distribution [113]. Self-assembly of amphiphilic molecules acting as surfactants is a facile method to produce organic nanoparticles. Researchers tried to extend the exfoliation method by stabilizing the exfoliated graphene in different solvents [114]. Various organic solvents, including N-methyl-pyrrolidone and dimethylformamide, have been used to stabilize nanomaterials to overcome this limitation [115,116]. The high boiling points of organic solvents lead to chemical degradation of nanomaterials and obscure their toxicity limits. This obstacle was circumvented by mixing amphiphilic surfactants with inorganic nanoparticles in water. When combined with organic solvents or oils, the hydrophobic components of these compounds form an internal structure that can transport hydrophobic compounds [117]. These hydrophobic components form an outer shell when they come into contact with the surrounding water. They can lower the surface tension between hydrophobic and hydrophilic regions and in this way stabilize the structure of nanoparticles [118]. The synthetic stabilizing substances commonly used in synthesis are hazardous and pose a significant environmental risk. The fabrication of stable, viable nanoparticles with accurate dimensions is a topic on which much remains to be discovered. Due to their high cost and tendency to generate harmful byproducts, synthesis techniques need to be replaced with efficient alternatives. For expedient synthesis of nanoscale materials, microbial surfactant-associated processes could be a good choice.

Top-down strategies using biosurfactants as capping and stabilizing agents have been proposed in a number of researches disclosing the fabrication of metallic nanocomposites, including Ag, Au, Cu, Pt, Pd, NiO, and ZnS, to limit or mitigate aggregation after and during the fabrication of the preferred nanocomposite [119]. Microbial and biosurfactant technologies for nanomaterial fabrication are still being developed because they are clean, safe, and environmentally friendly. These molecules also act as stabilizers and help to maintain a regular shape because of the electrostatic attraction forces [120]. In the studies [121,122], it is mentioned that the outer surfaces of nanoparticles coated with surfactants are used to prevent pollution, and it is confirmed that the use of nanoparticles coated with surfactants is a reusable, efficient and simple technique to remove a number of contaminants from water bodies. According to Gomez-Grana et al. [123], biosurfactants possess two functionalities that make them useful in the field of nanotechnology as reducing agents and stabilizers. Rhamnolipids have been shown to be used in various industrial applications such as coatings for cosmetics and tertiary petroleum extraction, food, horticulture, and in the expanding field of nanotechnology [124]. This approach takes into account the type of solvent and reducing agent used, as they are less toxic substances that also prevent particle aggregation and have the added advantage of being less harmful to the environment. The most typical strategy is to use stabilizing compounds that can be absorbed on

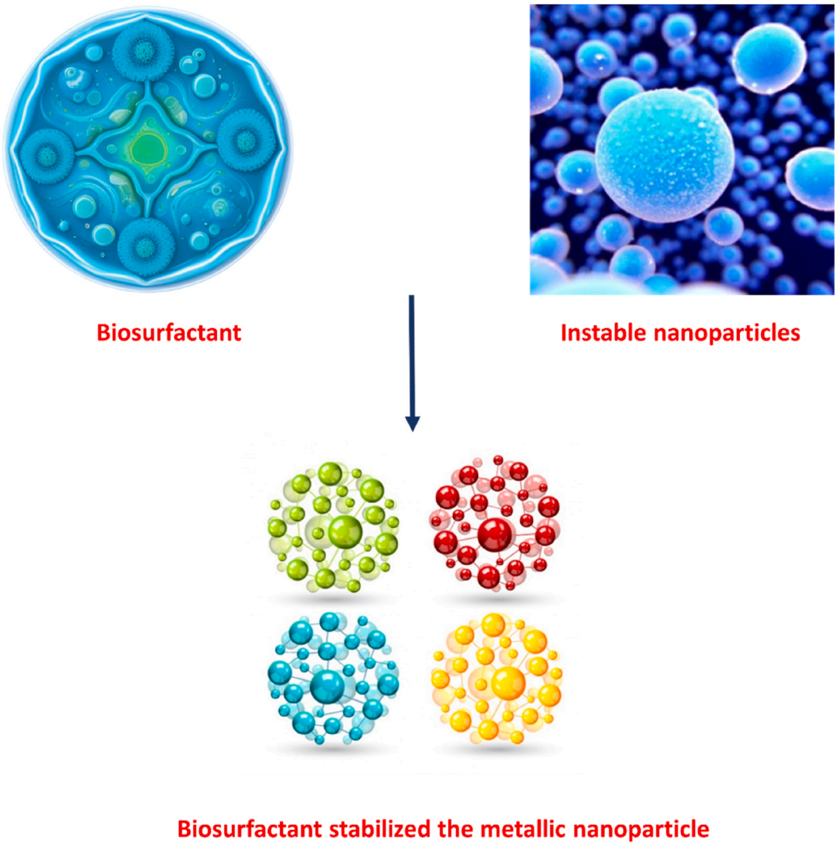

Fig. 3. The role of biosurfactants in the stabilization of various metallic nanoparticles.

the surface of the NPs to prevent their agglomeration. Capping agents or surfactants such as chitosan, gluconic acid, cellulose, or polymers can be used to stabilize and limit the aggregation and degradation of NPs [125–127]. A wet-chemistry approach was employed by Wang et al. [128] to synthesize ZO, utilizing Carboxy methyl cellulose as a surfactant. The resulting nanocomposites were then assessed for their efficacy in the adsorptive and photocatalytic removal of methylene blue from aqueous solutions. The formulation of a semi-solid mixture containing bismuth oxide nanoparticles was carried out by combining the synthesis of bismuth oxide nanoparticles with the formulation of the semi-solid. The synthesis of bismuth oxide nanoparticles involved the use of sorbitol as an intermediate under optimized conditions [129]. Many plants contain natural surfactants that are capable of absorbing, foaming, and dispersing. Plant-based biosurfactants are biodegradable and nonpolar, which makes them an attractive substitute for synthetic surfactants. Another environmentally friendly option for the production of nanoparticles is the use of plant-based surfactants [130]. In the plant extract, the biosurfactant molecules act as stabilizers or reducing agents.

Since microbial surfactants readily form a variety of liquid crystals in aqueous solution, they can be used to prepare highly efficient nanomaterials. Fig. 3 describes the stabilization of metallic nanoparticles using biosurfactants. The use of microbial surfactants has many advantages over chemical materials, including their biocompatibility, environmental friendliness, chemical stability, good selectivity, and binding ability under various environmental conditions [131]. The use of microbial surfactants is a particularly promising technique to reduce the neurotoxicity and gastrointestinal problems caused by synthetic surfactants. The concepts of microbial surfactants are reviewed in this paper, focusing on their potential use as novel nanoscale particles. The aim of this article is to thoroughly review the current status of biosurfactants, their advantages, and the main process parameters involved in the stabilization of metallic nanoparticles. In addition, several interesting applications of biosurfactants for nanoparticle stabilization have been discussed, which have attracted considerable interest in recent years and are presented in Table 3.

3. Types of nanoparticle

A number of characteristics, including as composition, size, shape, and origin, can be used to categorize nanoparticles. Based on the material composition, nanoparticles can be classified into two basic groups: organic and inorganic [147]. Carbon-containing substances make up organic nanoparticles, which are frequently linked to synthetic or biological polymers. Among the several types of organic nanoparticles are dendrimers, polymeric nanoparticles, lipid nanoparticles, and protein-based nanoparticles. Because of the ingredients that make up inorganic nanoparticles, which are not carbon-based, they have a variety of features. Quantum dots and metallic and oxide nanoparticles are a few examples [148]. The detailed about metallic nanoparticle are described below.

3.1. Silver nanoparticle

Silver nanoparticles (AgNPs) are used in a number of applications due to their low toxicity, inorganic nature and antimicrobial properties [149,150]. It is important to understand the requirements for the manufacturing processes so that the properties of AgNPs can be tailored in the desired way by modifying synthetic elements that are specifically made for a particular use. They are widely used in consumer products such as detergents, pastes, meals, textiles, and clothes because they have excellent antibacterial and antifungal activity against various species [151,152]. Due to the large surface area in silver nanoparticles, it decomposition of bacterial cells because the nanoparticles can penetrate the bacterial cells more easily. These NPs have been shown to have significant antibacterial activity against a variety of microorganisms. The above properties of silver nanoparticles can be used in high performance drug carrier applications. In addition, AgNPs are claimed to promote plant development.

Nowadays, the preparation of nano-sized AgNPs is carried out by various methods, including chemical and photochemical reduction processes, inverted micelles, the lamellar liquid crystal method, aerosol and electrospraying approaches [153]. Colloidal

Table 3
Effect of biosurfactants as capping agents in the synthesis of nanoparticles.

Metallic Nanoparticle	Capping agent (Biosurfactant)	Size	References
Silver	Rhamnolipid	1 nm	[120]
		166 nm	[132]
		20 nm	[133]
	Lipopeptide	44–70 nm	[134]
		3–30 nm	[135]
		21 nm	[136]
	Surfactin	17.8 ± 9.8 nm	[137]
Zinc sulphide	Rhamnolipid	10–15 nm	[138]
Zinc oxide	Rhamnolipid	6 nm	[139]
Iron	Rhamnolipid	23 nm	[140]
		38 nm	[141]
	Surfactin	8 nm	[142]
	Sophorolipid	100 nm	[143]
Gold	Lipopeptide	58.4 nm	[123]
		40–60 nm	[144]
Copper	Rhamnolipid	0.25 nm	[145]
Nickel	Rhamnolipid	11.6 to 47 ± 5 nm	[146]

consistency and agglomeration must be established, maintained and avoided for successful antibacterial and medical applications, as lack of stability leads to loss of antimicrobial property [154]. Enhancing the bioactivity of AgNPs through green synthesis methods involves functionalization with enzymes, polymers, or metal ions and is becoming increasingly popular as it can reduce or eliminate risks and improve biocompatibility for use in environmental applications [155,156].

Sophorolipids, derived from yeast, have also been demonstrated to stabilize silver nanoparticles. They form a coating on the nanoparticle surface, enhancing their stability and dispersibility in aqueous solutions. Using lipopeptide-biosurfactant micelles, the uniformly distributed AgNPs with excellent stability were prepared by Bezza et al. [136]. With minimum inhibitory concentrations (MIC) of 15.625 gmL^{-1} against Gram-negative *Pseudomonas aeruginosa* and Gram-positive *Bacillus subtilis*, the lipopeptide-stabilized AgNPs exhibited excellent antibacterial activity. A sustainable solid-state process and a solvent-free atmosphere were successfully used to prepare rhamnolipid-stabilized AgNPs [157]. With longer growth time in rhamnolipid medium, the absorption of AgNPs stabilized by rhamnolipids steadily increases by supporting the expansion of particle size. Farias et al. [120] prepared silver nanoparticles with a size of 1.13 nm using the biosurfactant of *P. aeruginosa* acting as a stabilizer. Rhamnolipid, a biosurfactant prepared from residues of refining vegetable oils and 2.5 % corn steep liquor, was found to be nontoxic and biodegradable. Durval et al. [158] synthesized silver nanoparticles (AgNPs) in an environmentally friendly manner by using a biosurfactant produced by *Bacillus cereus* UCP 1615 as a stabilizer. The diameter of the generated nanoparticles was determined to be about 20 nm. The AgNPs produced using biosurfactants have shown considerable antibacterial and antifungal activity, suggesting that they can be used as an alternative to conventional antibiotics. Silver nanoparticles (AgNPs) derived from plant extracts have demonstrated remarkable antiparasitic efficacy, displaying a reduced treatment duration and improved capacity to hinder parasite multiplication in comparison to conventional antiparasitic medications [159]. Numerous investigations suggest that silver nanoparticles prove advantageous in Photodynamic Therapy (PDT) owing to their exceptional stability, tunable size, optical characteristics, and ease of surface functionalization [160].

3.2. *Iron nanoparticles*

Numerous studies have focused on iron nanoparticles, known as zero-valent nanoscale iron (NZVI), because of their effectiveness in remediating aquifers contaminated with heavy metals, nitrates, phosphates, and other hazardous substances. Due to their superparamagnetic properties, iron oxide nanoparticles are widely used for various applications. There are numerous applications in biomedical therapy, hazardous waste treatment, groundwater treatment, adsorption process, catalytic process, and magnetic recording; iron nanoparticles have been extensively researched in recent years [161]. There are numerous methods to prepare iron nanoparticles, including the chemical method, co-precipitation, hydrothermal method, and sol-gel method [162,163]. However, their practical applications were limited by weak van der Waals forces and intrinsic magnetic attractive forces, which complicated their distribution in the environment and their interaction with certain pollutants [164]. As a result, numerous researchers focused on modifying the stabilizers on the surface of nZVI to improve its stability and size distribution. The mainly used stabilizers followed three types of stabilization to improve the efficiency of pure nZVI: electrostatic, steric, and network stabilization [165].

The primary function of biosurfactants in stabilizing iron nanoparticles is due to their capacity to adsorb onto the surface of the nanoparticles and create a protective coating. This layer offers steric hindrance and electrostatic repulsion between particles, which successfully inhibits iron nanoparticles from aggregating. Khalid et al. [82] demonstrated a simple approach for the preparation of rhamnolipid (RL)-coated iron NP and proposed a synergistic antibacterial and antiadhesive mechanism against *P. aeruginosa* and *S. aureus* biofilms. Reactive oxygen compounds are mechanically generated by RL-coated iron NP (48 nm), which support the antibacterial effect. By altering the surface hydrophobicity of the nanoparticles and thereby enhancing their anti-biofilm property against the two aforementioned strains, the RL shells significantly reduce cell adhesion. The iron nanoparticles were stabilized with surfactin produced by *Bacillus natto* TK -1 according to Liao et al. [142]. The results showed that the iron nanoparticles did not aggregate or change in size. The resulting nanoparticles have a narrow size distribution with a diameter of about 8 nm. Sangeetha et al. [141] described the techniques to modify iron nanoparticles with biosurfactants such as surfactin and rhamnolipid. The coated compounds located on the surface of the nanoparticles lead to significant changes in the surface potential and physical size. Sang et al. [166] investigated three relative concentrations of Ni (II)-contaminated soil for their ability to be immobilized using zero valent iron nanoparticles modified by rhamnolipid. Characterization data showed that the rhamnolipid was tightly bound to the nZVI and exhibited improved stability and size distribution. FTIR studies suggest that rhamnolipid and nZVI interact through chelation between carboxyl groups and nZVI or hydrogen bonding with Fe–O groups on the nZVI surface. The results support the hypothesis that the biosurfactant stabilizes nZVI and offers an intriguing prospect for the adsorption of Ni-contaminated soil.

3.3. *Copper nanoparticles*

Copper nanoparticles have recently received more interest and attention due to their well-defined properties, such as good redox potential, higher specific surface areas, good electrochemical properties and great reliability in solutions [167]. Copper nanoparticles are recommended among all nanoparticles due to their excellent optical and electrical transmission properties. Water purification method greatly benefits from the remarkable antibacterial properties of copper oxide nanoparticles as they eliminate a variety of pathogens [168]. It is generally accepted that the production of these metallic nanoparticles is inexpensive, environmentally safe and easily accessible [169]. Due to their ubiquitous use in electronics, sensor devices, catalyst support and medical applications, metallic copper, copper oxide (CuO), and cupric oxide (Cu_2O) nanoparticles have recently attracted much attention [170,171]. Compared to other metals such as gold and silver, copper nanoparticles are abundant and inexpensive, favoring their use in various fields [172].

The main disadvantage of nanoscale copper nanoparticles is that they do not achieve sufficient stability due to their strong tendency to agglomerate and form complex clusters [173,174]. After cluster formation, a rapid sedimentation process occurs, which leads to a loss of sensitivity. Biosurfactants prevent the aggregation of copper nanoparticles by producing a covering around them that acts as a repulsive force between the particles. The dispersal effect contributes to the stability and uniqueness of the nanoparticles in solution. Copper oxide nanoparticles (Cu_2O NPs) were prepared by Bezza et al. [175] using a lipopeptide biosurfactant as a stabilizing agent. This Cu_2O NP showed a minimum inhibitory dose of 62.5 gmL^{-1} at pH 5 against Gram-positive and negative bacteria. These results indicate that these surfactant-activated nanoparticles can act as a biocompatible antibacterial and pharmaceutical agent.

3.4. *Gold nanoparticles*

The preparation of gold nanoparticles (AuNPs) for various uses in chemical processes has recently attracted more attention [176–179]. Oxidation processes, gasification reactions and cross-coupling reactions are the main applications of AuNPs [180–183]. Due to their ease of preparation, harmlessness, excellent bioactivity and special optical properties, AuNPs are essential for bio-nanotechnology. By adjusting the nanoparticle size, the optical properties of AuNPs can be tuned. Ionic strength and thickness are the two factors that determine the diameter of AuNPs. When the reducing agent is not able to stabilize the particles, surfactants are use d in the preparation of AuNP [184]. Sodium borohydride and sodium citrate are the standard oxidizing agents that stabilize AuNPs in the absence of surfactants. However, these nanoparticles are not very useful for in vivo applications because the oxidized metabolite of the reducing agents is itself neurotoxic [185]. The use of biocompatible methods to generate AuNP using a biomolecule as a reducing agent is widespread.

In response to the growing demand for gentle, non-hazardous and environmentally safe technologies for the synthesis of AuNPs, biosynthetic processes have been developed using either biosurfactants as ecologically responsible substitutes for chemical surfactants. Control over the size, shape, and morphology of gold nanoparticles can be achieved by using certain biosurfactants as templates or surfactants during their production. The total stability and homogeneity of the population of nanoparticles is enhanced by this carefully managed synthesis process. In the study by Reddy et al. [186], an anionic biosurfactant called Surfactin-capped AuNP was prepared for the first time. The lipopeptide surfactin used to hold the gold nanoparticles in the aqueous phase which undergoes structural changes as a result of varying proton levels; the effects of these changes on the shape of the nanoparticles were studied. At a pH of 5–9, the images from TEM, showed that the mean size of the particles was about 13.11, 8.16, and 4.70 nm. Bakur et al. [187] presented an approach to prepare AuNPs using glycolipid from *Ustilago maydis* and evaluated the biological activities of these AuNPs. The biologically synthesized AuNPs significantly inhibited cell proliferation of pathogenic organisms of Gram-positive and Gram-negative bacteria. Gold nanoparticles (AuNPs) stand out as potent tools in crafting highly sensitive electrochemical biosensors [188]. Their distinct capabilities, serving as an efficient platform for biomolecule immobilization and promoting electron transfer between the electrode surface and immobilized molecules, position them as promising candidates for biosensor applications. The use of AuNPs-modified electrodes holds the potential to enhance sensitivity and lower limits of detection in comparison to unmodified electrodes.

3.5. *Cadmium sulphide nanoparticles*

Cadmium sulphide nanoparticles (CdS NPs) have distinct optical features and controllable photoluminescence properties. Cadmium is a metallic element with exceptional corrosion resistance and high electrical conductivity. CdS material is also found in colloidal and fluorescent semiconductor crystals called CdS quantum dots. In battery systems, circuits and other electrical devices, CdS nanoparticles or quantum dots are widely used. Due to their distinct ability to glow, cadmium nanoparticles are used as fluorochromes and biomarkers [189]. However, the use of these quantum dots for biological applications has been limited due to the time-consuming fabrication process and the use of various hazardous chemicals. The various forms of CdS NPs are synthesized using different techniques and tested against a variety of microbial properties [190]. Since most of the properties of the semiconductor NP depend significantly on the size, pore diameter, and crystalline structure, most studies have focused on changing the shape and size of CdS NPs. Various methods, including the laser method, the evaporation process, and templates, have been used to create CdS NPs with a variety of shapes and morphologies [191]. Using the special qualities of these biomolecules, biosurfactants can stabilize cadmium sulphide (CdS) nanoparticles by preventing aggregation and enhancing the dispersion of the nanoparticles in solution. Singh et al. [192] investigated the isolation of surfactin from *Bacillus amyloliquifaciens*, which was used to produce cadmium sulphide nanoparticles. Surfactin was shown to play an important stabilizing and capping role in the data, which also caused a phase transition to form CdS nanoparticles with an average size of 3–4 nm. The discovery of biological quantum dot synthesis lowered the amount of hazardous chemicals while opening new biological applications.

3.6. *Nickel nanoparticles*

There are potential applications for nickel nanoparticles in various industries such as telecommunications, electromagnetism, power generation, and healthcare [193]. Nanoparticles are widely used in the environment for adsorption of toxic dyes and inorganic substances and play an important role in maintaining a clean environment [194,195]. They are also used in biomedicine due to their effective antimicrobial and anti-inflammatory properties [196]. Nickel nanoparticles are of great interest because of their use in catalysts, electrical conductors, and metallic alloys. The shape change of these cells after treatment with NiNPs suggests that they also exhibit cytotoxicity against malignant cells. Few studies have been published on the preparation of NiNPs, and these have generally been performed in organic media to prevent the formation of nickel oxide or hydroxide [197].

Biosurfactants facilitate the dispersion of nickel nanoparticles and inhibit sedimentation or precipitation by lowering the solvent's surface tension. Rhamnolipid biosurfactant was used by Palanisamy [198] to stabilize nickel oxide nanoparticles (NiO NP). Two different microemulsion methods were used to prepare the nanorods. These nanorods were measured to be 150–250 nm in length and 22 nm in size. Palanisamy and Raichur [146] used the same slant to prepare uniformly distributed NiO NP in spherical shape. The size of the nanoparticles decreases as the pH of the solution increases. At pH values of 11, 12, and 12.5, NiO nanoparticles with sizes of 86, 63, and 47 nm were produced.

3.7. Zinc sulphide nanoparticles

ZnS quantum dots (QDs) have numerous applications in nonlinear optical systems, photocatalysis processes, photoluminescence, and optical switches. Due to their non-toxic properties, ZnS quantum dots are now being used for wastewater treatment. In this process, they act as a photocatalyst and break down a number of impurities, such as organic contaminants. These factors have led to research documenting a variety of physical and chemical processes for producing different types of ZnS. However, environmentally responsible and economically advantageous biological synthesis methods are available for the production of ZnS-NP. Methods such as thermal oxidation, water micelles, inverted micelles, and the sol-gel process have been used [199].

ZnS nanoparticles' surface characteristics can be changed by biosurfactants, which reduce particle aggregation and prevent agglomeration, improving stability. This alteration facilitates the dispersibility of nanoparticles in different matrices or solvents. Moreover, Hazra et al. [138] demonstrated the biotransformation of zinc sulfide (ZnS) nanoparticles with rhamnolipid biosurfactant caps. Their phase structure, bioactivity, anticancer activity and ability as nanophotocatalysts for the degradation of textile azo dyes were also described. In the preparation of zinc nanoparticles, pure rhamnolipid was used as a capping agent in the synthesis. The efficacy of ZnS nanoparticles in decolorizing brown textile dyes was quite good, and it was also found that encapsulation of nanoparticles with biosurfactants reduced their toxicity. *Pseudomonas aeruginosa* produced water soluble rhamnolipids were used by Narayanan et al. [200] to encapsulate ZnS NP and they emphasized metal affinity, morphology and optical properties. They were very stable and well soluble in water and were made available in an aqueous system without the use of any organic solvent. The FT-IR results of ZnS nanoparticles with rhamnolipid caps showed affinity between the COOH group of the biosurfactant and the metal ions. The accurate measurements showed that the nanoparticles have a limited size distribution with a radius of about 4.5 nm. According to the scientists, zinc nanoparticles capped with biosurfactants have greater potential for the next generation of nanoparticles.

4. Conclusion and future outcomes

Recently, the application of surfactant molecules on metallic nanoparticles has been considered as an environmentally friendly way for the stabilization process. Moreover, the coating of biosurfactants with metallic nanoparticles makes them useful in nanotechnology as reducing agents and stabilizers. These biosurfactants provide an opportunity to overcome the challenges of nanotechnology, such as inefficiency, aggregation, and degradation of nanoparticles. Since the biosurfactants are non-toxic compared to the chemical stabilizers, they reduce the negative impact on the environment. This study provides useful information on the stabilization of metallic nanoparticles using biosurfactants, which supports the use of these particles in environmental applications. Biosurfactants are expected to gain importance as multipurpose materials in the coming decades. However, the fundamental technological barrier to commercial use remains the manufacturing costs associated with biosurfactants, particularly with respect to downstream processes. Therefore, future research aims to develop biosurfactants in a less costly manner by using renewable substrates. This review provides an outlook on the development of various metallic nanoparticles by coating with biosurfactants, which help to overcome the limitations of nanoparticles that do not allow aggregation and do not change the properties of nanoparticles. Thus, maintaining the properties of metallic nanoparticles depends on their stabilization. The combination of nanotechnology with biosurfactants promises to open up new possibilities in this field. Biosurfactants are in a unique position to shape the future of nanotechnology because of their mix of biocompatibility, efficient stabilization, and environmental conscience. Maintaining the homogeneity and purity of biosurfactants during large-scale manufacturing can be challenging, which affects how well they stabilize nanoparticles. Particular industrial processes may be limited in their usage of particular biosurfactants due to their limited stability in harsh environments, such as high temperatures and extreme pH levels.

CRediT authorship contribution statement

Femina Carolin C: Resources, Methodology, Conceptualization, Investigation. **Kamalesh T:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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