# Microbiologically Synthesized Nanoparticles and Their Role in Biofilm Inhibition

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**Abstract**

Much research is being done on alternative antibacterial therapies that replace or supplement conventional antibiotics since multidrug-resistant bacterial infections are becoming more prevalent. Metallic nanoparticles have been demonstrated to destroy bacterial biofilms successfully. However, their chemical manufacture frequently results in harmful byproducts. Recent research has shown that the environmentally friendly production of metallic NPs may be accomplished using microbial and plant extracts. The NPs can effectively limit bacterial growth by passing through the exopolysaccharides of a biofilm matrix. A cluster of sessile microbial cells forms a biofilm group that may cling to surface biological and nonliving things, through glycocalyx and additional polymeric molecules. Such biofilms result in biofouling on implants and medical equipment and several chronic disorders. NPs that penetrate the biofilm change the QS gene pathways, impairing cell-to-cell communication and preventing the formation of the biofilm. Algae, which create a variety of biogenic chemicals, have been discovered to be capable of destroying biofilms without negatively affecting the ecosystem and other biotas. The main component of the algal extract with antibacterial and anti-biofilm properties is polyunsaturated fatty acids. The extracts from roughly 225 different species of cyanobacteria and microalgae exhibit anti-biofilm action. This section is focused on the "signal jamming effects" of different metallic and nonmetallic nanoparticles produced by microbial nanotechnologies on biofilms' development.

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N. R. Maddela et al. (eds.), *Microbial Processes for Synthesizing Nanomaterials*, Environmental and Microbial Biotechnology,
https://doi.org/10.1007/978-981-99-2808-8_13

## 13.1 Introduction

Most severe diseases in people are discovered in biological origin. According to Costerton et al. (1999), a biofilm is a microbial cell's symbiotic relationship. That continues to be attached to surfaces, whether biological or nonliving things, that include self-produced hydrated polymerized compounds. The growth of biological material is generated by bacteria in the plankton sticking to surfaces like those of medical equipment and prosthetics. In addition, it promotes the development of wound-associated infections, chronic otitis media, cystic fibrosis, and valve endocarditis (Donlan 2001; Santos et al. 2011; Abidi et al. 2013).

The method of cell-to-cell communication, which is concentrated and reliant on direct communication of chemical substance transfer (Lobedanz and Søgaard-Andersen 2003; Phelan et al. 2012), chemical signaling (Eberhard et al. 1981), and electrical signaling determines the capacity of bacterial cells to adapt and monitor a variety of environmental situations (Nielsen et al. 2010; Shrestha et al. 2013).

Quorum sensing is the name given to communication that is a density-dependent mechanism that is activated by minute molecules in bacteria (autoinducers) (QS). Initially, this process was noticed in *Vibrio fischeri* (Nealson et al. 1970), and Fuqua et al. (1994) created the acronym QS. Acyl-homoserine lactones (AHLs), a class of autoinducing peptides crucial in developing bacterial pathogenicity, make up the QS machinery. Exotoxin A, lection, pyocyanin, and elastase are only a few virulence factors generated by QS in *Pseudomonas aeruginosa*, In contrast, *Staphylococcus aureus* was shown to have protein A, enterotoxins, lipases, hemolysins, and fibronectin (Yarwood et al. 2004; Carnes et al. 2010).

Bacterial cells can avoid the pathogenicity of the host defense system with virulence determinants that have evolved. The transcription of several genes in the poly-step process that leads to the creation of biofilm is the planktonic stage of microbes from a single organism (Donlan 2002). The transformation of planktonic organisms into their sessile forms enhances numerous chemical compounds, which causes genetic alterations in the cells. The dense extracellular polymeric substance (EPS), made up of the sessile microcolonies, produces proteins, extracellular DNA, and other polymerized components that act as a natural barrier all around microbial cells. The quorum sensing (QS) pathway causes the biofilm to mature (Lahiri et al. 2019).

Lahiri et al. (2019) claim that the unpreventable attachment of microbial cells to the surface, the yield of QS compounds, the movement of materials inside the biofilm, the metabolic activity of the substrate by various immobile microcolonies, the progression of EPS, and eventually the metastasis of the sessile colonial possessions are the causes of the development of biofilm. Although antibiotics are the first choice to treat microbial diseases, the rapid rise in bacterial resistance due to uncontrolled antibiotic usage has emerged as a major health issue (Laxminarayan et al. 2013; Chioro et al. 2015; Zhao et al. 2017; Zhong and Zhao 2018; Ma et al. 2019; Sarkar et al. 2020).

A conventional method for treating biofilm consisted of combining several antibiotics with various killing mechanisms. However, because of the rise in antibiotic resistance, standard medications cannot prevent biofilm development. The growth of EPS surrounding the microcolonies hinders or completely stops the spread of antibiotics inside the system of life. Growth of EPS surrounding microcolonies inhibits penetration, resulting in zero or little antibiotic dispersion within the physical system. Additionally, changes to the microenvironment inside biofilm matrices lead to establishing a concentration gradient of metabolites that inhibits or almost eliminates bacterial growth.

Additionally, it has been noted that changes in the microenvironment cause the nutrient supply to change, oxidative stress to be produced, water to become scarce, starvation to occur, and temperature to change, all of which cause the bacterial cells to develop a variety of stress-related adaptive mechanisms (Singh et al. 2017). Change of the microbial cells follows this into persisters. It also plays a big part in the development of drug tolerance. Persisters are a highly protected spore-like condition (Stewart 2002).

Various nanoparticles (NPs) have recently gained popularity as an alternative to antibiotics in treating bacterial infections. Nanoparticles act by bypassing drug resistance mechanisms in bacteria and inhibiting biofilm formation or other important processes related to their virulence potential. NPs have a completely different method of new strategies have emerged to attack bacteria without having to enter the microbial cell (Wang et al. 2017a). The production of nanoparticles by microbiology is shown to be more advantageous than that through chemical modification because it does not necessitate the same circumstances as a purified precursor material. The requirement of favorable circumstances and suitable temperature ranges (20–30°C) increase the viability of bacteriologically manufactured NPs in the marketplace (Vaseghi et al. 2018). Furthermore, a natural capping factor acts as a barrier toward oxidation, agglomeration, and clustering on certain microbiogenic nanomaterials, providing outstanding persistence (Durán and Seabra 2012). As a result, NPs created through microbiology are generally thought of as being preferable to antibacterial therapy (Capeness et al. 2019; Prasad et al. 2020; Maddela et al. 2021; Inamuddin et al. 2021; Saglam et al. 2021).

## 13.2 Synthesis of Microbial Nanoparticles

Owing to their elastic physicochemical properties, nanoparticles (NPs) have lately revolutionized employment in the health sector by introducing new properties, including thermal and electromagnetic conductivities, absorptivity, melting temperature, and the improvement of catalytic efficiency by altering the surface-to-volume ratio. Nanotechnology includes the production of nano-dimensional materials with different form- and size-dependent properties (Rafique et al. 2017). In the health sector, many NPs, particularly silver nanoparticles (AgNPs), display a wide range of applications, including the capacity to distribute medications, use biochemical detectors for medical imaging, and catalyze reactions. Other uses include memory chips, wireless electrical logic, computer transistors, and antibacterial effectiveness (Das et al. 2014; Prasad 2014; Prasad et al. 2018; Aziz et al. 2014, 2015, 2016, 2019).

The traditional techniques for producing NPs include ultrasonication, radiolysis, microwave, spray pyrolysis, electrospinning, the sol-gel method, chemical reduction, and inert condensation. However, the immediate demand for a quicker, cheaper, more effective, nontoxic, and environmentally friendly procedure has turned attention to greener methods (Khandel and Kumar-Shahi 2016; Fang et al. 2019).

The stabilization of NPs is effectively aided by biogenic sources such as bacteria, fungi, and other plant components (Durán et al. 2005). Microorganisms like fungus, yeast, and bacteria are used in the green synthesis of NPs as the process may be adjusted by changing the culture parameters, such as nutrition, pH, pressure, and temperature. The microbial system has an internal mechanism for producing nanoparticles (NPs) from metallic salts (Li et al. 2011; Prasad et al. 2016; Srivastava et al. 2021; Kisimba et al. 2023).

Studies have indicated that heavy metals being transformed into metallic NPs involve bacterial cells significantly. The creation of metallic NPs is caused by various interacting pathways present within bacterial cells. Bacterial cells can create sustainable nanoparticles on a vast scale, another benefit of using them (Fariq et al. 2017). Additionally, it has been shown that cells have subcellular enzymes that are involved in the generation of nanoparticles, especially in fungi (Fariq et al. 2017). Enzymes like nicotinamide adenine dinucleotide (NADH)-dependent reductase were used to synthesize metallic nanoparticles (Guilger-Casagrande and de Lima 2019; Prasad 2016, 2017).

The enzyme nitrate reductase and anthraquinones from *Fusarium oxysporum* had the responsibility of decreasing the silver ions. In a different work, extracellular NADH-dependent nitrate reductase was applied to create AgNPs utilizing identical fungi and quinolones (Anil Kumar et al. 2007). AuNPs are also created by a fungus enzyme called NADH-dependent oxidoreductase (Kitching et al. 2015). Furthermore, studies showed that the creation of NPs included the enzymes nitrate reductase and alpha-NADH-dependent reductase.

The output of NPs is often higher in fungi than in bacterial cells because they have more biomass. Although bacteria are more frequently utilized to make metallic NPs, the presence of mycelia in fungi may make them more valuable since they offer a larger surface area for interactions. Because fungi generate more enzymes than bacteria, turning metallic salts into metallic NPs happens more quickly. The metal ion absorption and reduction mechanism for the generation of NPs included the fungal cell wall (Khandel and Shahi 2018).

The interior elements of fungal cells, such as the cell wall, cytoplasmic membrane, protein, enzymes, and others, are crucial in the formation of the nanoparticles. The synthesis of AgNPs and other metallic NPs is affected by temperature, pH, biomass, and additional physiological characteristics. These nanoparticle antimicrobial (antibacterial, antifungal, and antiviral) capabilities, among other features, benefit human welfare. In actuality, no harmful substances are needed for the NP recovery and purification procedure since the method of biosynthesis of AgNPs by fungus or materials derived from fungi (Wei et al. 2009).

Mycogenic AgNPs do, however, have several drawbacks similar to other nanoparticles. Before use, it is essential to verify AgNPs' biocompatibility and biosafety, particularly in the healthcare industry. The majority of the known fungi species for producing nanoparticles have been documented will become harmful to both humans and plants, which poses the biggest challenge to the commercial production of myogenic metallic NPs. *Trichoderma reesei*, on the other hand, is a nonpathogenic fungus that has gained widespread acceptance for the production of AgNPs as an industrially suitable strain (Dorcheh and Vahabi 2016).

Higher manufacturing costs and greater biosynthesis times are other downsides of NPs produced by a fungus (Jeevanandam et al. 2016). Utilizing bacteria to produce NPs has the benefit of rapid growth and a more straightforward technique for controlling genetic expression (Lovley and Woodward 1996). Owing to their ability to withstand settings with higher levels of metallic particles, bacteria are frequently used to synthesize metallic NPs (Haefeli et al. 1984).

## 13.3 Microorganism-Assisted Nanoparticle Synthesis Mechanism

Microorganisms can produce nanoparticles (NP) intracellularly and extracellularly by synthesizing metals, metal oxides, or metalloids. In the literature, this procedure is well-documented (Patil and Chandrasekaran 2020). The extracellular process includes the discharge of metal ions for nanoparticle production by bacterial enzymes and proteins of microbial or fungal cell wall constituents or organic compounds present in the growth media. This is in contrast to the subcellular mechanism, which includes the early electrostatic interaction of metal ions by carboxylic acid groups of the bacteria cell wall, channel of metallic ions via cells, and reduction by subcellular proteins and cofactors to generate NPs (Siddiqi et al. 2018; Koch et al. 2023).

It is possible to identify bacterial resistance pathways for cellular detoxification in the biochemical processes involved in microorganism-mediated nanoparticle production. In this, enzyme, mediated degradation and nanostructure-based deposition change the dissolution of inorganic and dangerous ions. It has been suggested that there are techniques for extra- and intracellular biocatalytic production. These mechanisms primarily involve oxidoreductase enzymes and cellular transporters, such as NADH-dependent nitrate reductase, NADPH-dependent sulfite reductase flavoprotein subunit alpha, and cysteine desulfhydrase (Grasso et al. 2019). Cellular enzymes transform hazardous metal ions further into appropriate metal elements by binding specific ions from the environment and biosynthesizing nanomaterials in microorganisms. Based on how they are made, nanoparticles can be classified as intracellular or extracellular. In the intracellular method, ions are introduced within the microbial cell where they combine with enzymes to create nanoparticles. In the extracellular state, reduced ions and metal ions are confined on the surface of the cell when enzymes are present (Li et al. 2011).

## 13.4 Microbial Enzymes' Nanoparticle Bioreduction of Metal, Metalloid, and Nonmetal Ions

Extracellular enzymes from various bacteria and fungi can convert metal and metalloids into the appropriate nanoparticles. Extracellular enzymes, like nitrate reductase, can transfer electrons from specific donors (such as hydroxyl groups to Ag+), facilitating the conversion of Ag+ to metallic AgNPs. Functional groupings, such as -$NH_2$,-OH,-SH, or –COOH, help in the stabilization of microbial proteins.

Microbiological proteins aid in the stability of metal ions, which are later transformed into NPs on the cell wall or within the periplasm, of the NPs by serving as interaction sites for those ions. When NPs are formed and stabilized, proteins sometimes act as primary reducing or capping agents. By transferring electrons between cytoplasmic elements (such as NADH/NADPH), vitamins, and organic acids, it is also known that internal enzymes such as cytochrome oxidases support the conversion of metal ions into NPs. There are three ways that subcellular reductase can initiate synthesis and stability of nanomaterials: periplasmic reductase can actively reduce $M^+$ to M, bioreduction takes place in the cytosol or periplasm and generates M from $M^+$or, $M^{2+}$ in the cytoplasm and M can be formed (Klaus et al. 1999; Mishra et al. 2017; Lv et al. 2018; Siddiqi et al. 2018).

$Te^{2+}$ and $Se^{2+}$ are poisonous metalloid species that degrade using toxic chemical reductants, which is terrible for the sake of the planet and human health (Presentato et al. 2018). As they produce little to no harmful byproducts during the whole degradation process their efficiency in disintegration, purification, and bioinspired reductants is one possibility. Rhodococcus, an actinomycete, breaks down $SeO_3^{2-}$ aerobically to create Se-NPs. Greater free energy and less stability in solutions caused, Se-nucleation seeds to be produced during the reduction of $SeO_3^{2-}$ to create Se-NPs, which were then assembled to form the suspension, and nanomaterials were precipitated as nanocrystals (Jana 2015). In a different investigation, the enzyme fumarate reductase with selenite reducing factor was used by *Enterobacter cloacae* to create Se-NPs both intracellularly and extracellularly. Microorganisms like *Citrobacter freundii* (anaerobic synthesis) and *Pseudomonas putida* could also produce Se-NPs (aerobic synthesis). During the earlier case, it is found that thiol-containing amino acids, such as cysteine, facilitate the chelate of $SeO_3^{2-}$, whereby creates Selena di-glutathione. As a substrate, this can cause glutathione reductase to produce the unstable intermediate Se0—additionally, microbiological species like *Stenotrophomonas maltophilia* SeITE02 and *Ochrobactrum* sp. MPV1 creates spherical nanoparticles of Se and Te. Black Te-NPs can be produced from tellurite using NADH-dependent reductase as a detoxifier (Song et al. 2017; Wang et al. 2017b; Xu et al. 2018).

With the aid of a few multicellular proteins, some bacteria, such as *Magnetospirillum magneticum*, have subcellular magnetosomes that help encapsulate Fe2O3-NPs in their dissolved state (e.g., ferritin or iron reductase enzymes). Biological membranes comprised of proteins, glycolipids, and phospholipids surround magnetic nanocrystals of the raw materials magnetite ($Fe_3O_4$) and greigite

($Fe_3S_4$) that are employed by *magnetotactic* bacteria to move through the earth's electromagnetic field. Environmental factors, cellular stress, and cell growth cycles influence magnetosome synthesis. As the magnetosomes develop, when the iron is transported *Magnetosomes* are oriented in a chain, crystals are created, and produced are mature outside of the bacterial cell membranes (Kuzajewska et al. 2020). Due to differences in composition, the magnetosome membrane contrasts with the plasmalemma and offers the right conditions for biomineralization. The magnetosome island produces distinct protein sets to control this tightly regulated process of magnetosome formation (Barber-Zucker and Zarivach 2017). At the junction of the magnetosome membranes, supersaturating quantities of iron also led to the formation of magnetite. Vesicle formation has been seen to take place before the biomineralization event. Thus, using the MamB and MamM proteins, as in the case of *Magnetospirillum magneticum*, could make it simpler to pump vesicles with iron at supersaturation levels. A better nucleation process is made possible by interactions between the crystal's ions and its surface proteins. The physicochemical characteristics of the magnetite nanoparticles were also discovered to have an impact on their shape including pH, redox potential, temperature, the route in which iron is supplied, the quantity of stimulator and inhibitory ions or molecules, and supersaturation state (Faivre and Schüler 2008).

The usual precursor for these metal oxide nanoparticles is $FeCl_3$. For instance, *Morganella morganii* and *Erwinia herbicola* bacteria were employed to create metal oxide nanomaterials of CuO and $SnO_2$, respectively, employing redox processes and enzymes like NADH. The freshly generated metal NPs can be reduced and stabilized by the metabolites of microbes in the fermentation broth secreted (Srivastava and Mukhopadhyay 2014; Obayemi et al. 2015).

Several researchers have created transition metal chalcogenide nanoparticles. For instance, *Moorella thermoacetica* can produce CdS-NPs extracellularly by adding $Cd(NO_3)_2$ to the medium for bacterial growth that promotes photosynthetic $CO_2$ into acetic acid. *Desulfovibrio caledoniensis* manufacture CdS-NPs both extracellularly and intracellularly. Anaerobic sulfate reduction in bacteria is activated by ATP sulfurylase in a three-step process that also needs ferredoxin or NADH to reduce the succeeding adenosine-phosphosulfate (APS) complex to sulfite and assimilatory or dissimilatory sulfite reductase to convert sulfite to sulfide. Regulating the amount of poly-ethene glycol in the *Clostridiaceae* sp. can also produce PbS nanocrystals, where the sulfate-reducing bacteria first convert (SO4)2- to $S_2$ followed by $S_2$ which will slowly combine with $Pb^{2+}$ to precipitate as PbS-NPs (Qi et al. 2016; Yue et al. 2016). Additionally, studies have revealed that *Shewanella oneidensis* MR-1 can create highly distributed Pd-Ag bimetallic NPs related to graphemes (Han et al. 2019). Crude polysaccharides derived from *Pleurotus* flagellates can transform graphene oxides into nanosheets (Dasgupta et al. 2017).

## 13.5 Microbial Exopolysaccharides for Nanoparticle Synthesis

Exopolysaccharides (EPSs) are produced extracellularly by bacterial cells and are essential for surface adhesion and cell-to-cell communication. In addition to having the capacity to create nanoparticles by reducing metal ions, EPSs also serve as a capping factor in stabilizing the NPs; thus, the EPSs act as a backup option for the microbiological creation of several metal nanomaterials. Bacterial EPSs, mostly made of noncarbohydrate components that give the EPSs their anionic nature, as well as carbohydrates such as D-glucose, L-fucose, D-mannose, D-galactose, and N-acetyl-D-glucosamine. Certain organic compounds typically produce EPSs are more lipophilic, affecting how well they interact with cations like metal ions. Chelated metal ions are diverse functional groupings that diminish and stabilize via electrostatic bonding after being in touch with EPS.

With -H bonding, the subsequent inhibition of their aggregation, and precipitation, the bonding in the nanoparticles stabilizes (Escárcega-González et al. 2018). To create NPs that have capping and chelating processes, various functional groups associated with Gram-positive and Gram-negative EPS function as stabilizing and lowering agents (Emam and Ahmed 2016). This helps to regulate the thickness, particle dispersal, and form of the NPs (Kanmani and Lim 2013). Mucoadhesion features help in the detection of non-specific protein transporters by the NPs allowing them to gain broader applicability (Kanmani and Lim 2013). Recent studies have demonstrated that the production of AgNPs involved the utilization of structurally characterized EPS from succinoglycan bacteria. *Sinorhizobium meliloti* produces a polymeric material that induces the aldehyde group to oxidize into a carboxyl group-mediated nucleophilic insertion in the reduction of the metal (Kwon et al. 2009). *Alcaligenes faecalis*, *Rhizobium* sp., and *Agrobacterium* sp. are the leading producers of curdlan, a different kind of EPS made up of (1, 3)-D-glucan repeating units connected by beta-(1, 3)-glycosidic linkages. Some are used in the synthesis and stabilization of nanoparticles (Zhang and Edgar 2014). To create derivatives of curdlan, a polymer that is insoluble in water can be carboxylated or oxidized. AgNPs were created by Leung et al. (2010) using carboxymethylated curdlan. It was easier to reduce the silver ions since the negatively-charged hydroxyl and carboxyl groups continued to exist. Another essential element of EPS that helps make graphene nanomaterials is dextran (Hu et al. 2016). Dextran is a multidimensional branched glucan produced mainly through some types of lactic acid bacteria, such as *Leuconostoc mesenteroides* and *Streptococcus mutans*. It is chemically made up of glucose residues linked together by alpha-(1,6) glycosidic bonds. Dextran, which worked as a stabilizing agent and reductant in an aqueous solution, was used to create size-controlled AgNPs by Bankura et al. (2012).

*Delftia acidovorans* and *Cupriavidus metallidurans* can also manufacture Au NPs greenly. The bacterial biofilms can be harvested for their gold nuggets (Johnston et al. 2013). The results from experiments revealed a nanoparticle Au could prevent the production of biofilms (Reith et al. 2010). By modifying the microbial cell membrane's surface chemistry, and hydrophobicity, they interact with lipids and proteins, and Au NPs prevent biofilm growth (Ikuma et al. 2015).

As a result, the NPs' ability to break through the biofilm is altered. The thickness of the nanoparticles, the surface charge, their chemistry, and their concentration all affect how well they can pierce the biofilm (Ikuma et al. 2015). Following that, the NPs interact with the biofilm's structural elements, which causes the biofilm to disintegrate (Qayyum and Khan 2016; Pinto et al. 2019). Furthermore, there is evidence that it's Au NPs changed groups can boost their ability to inhibit one or more types of biofilm cells. The biofilm can be efficiently interfered with by various factors, including Van der Waals, hydrogen bonds, electrostatic contacts, and hydrophobic interactions (Yu et al. 2018).

## 13.6 Microbial Biosurfactants for the Production of Nanoparticles

Biosurfactants are amphiphilic compounds with microbial surface activity primarily made by bacteria, fungi, and yeasts. The majority of its hydrophilic component is made up of long-chain or hydroxyl fatty acids. In contrast, their hydrophobic moiety comprises carbohydrates, cyclic peptides, amino acids, carboxylic acids, or phosphates. Glycolipids, lipopeptides, and phospholipids are examples of low-molecular-weight surface active agents (LMW). High-molecular-weight polymers, also known as bio-emulsifying agents like emulsan, are the two categories into which these are separated (Pati et al. 2020). They can alternatively be categorized as (a) glycolipids (rhamnolipids); (b) Mycolic acids, which are hydroxylated and cross-linked fatty acids; or (c) lipopolysaccharides. When metallic nanoparticles are synthesized using biogenic methods, biosurfactants can serve as good capping agents (Płaza et al. 2014). They work by adhering to metallic nanoparticles, stabilizing their surfaces, and preventing future aggregation, all of which contribute to stabilization (Kiran et al. 2011; Gahlawat and Choudhury 2019). Hydrophobic and hydrophilic molecular combinations in classes of amphipathic molecules biosurfactants divide variously polarized fluid stages with hydrogen bonding at their interface (Rodrigues et al. 2006). Microemulsions are water-solvable droplets, which serve as a micro-reactor. The droplet's size decreases as the surfactants' concentration rise, lowering the thickness of the particles. There being water significantly influences the size and form of the NPs. The molar ratio of water (R) determines the particle thickness and mono dispersity (Han et al. 2008).

## 13.7 Microbial Nanoparticle Synthesis via Biomineralization

Few microbes can reduce metal salts producing metallic ions that concentrate either within or without the microbial cells, mobilizing or immobilizing the salts of metal. They change the metals' oxidation condition through electrochemical reactions to achieve complexation and inactivation, followed by their precipitation, with the aid of efflux pumps.

For instance, gold (I)-thiosulfate is metabolized by *Acidithiobacillus thiooxidans* cells into Au(I) and thiosulfate (S2O32-) ions. Whenever Au (I) degrades to atomic gold inside the cells, thiosulfate is an energy source. This atomic gold precipitates within the microbial cells to create NPs throughout the late stationary stage and is subsequently liberated from the cells. Finally, the bulk solution's gold particles are turned into the wire at micron scales and octahedral gold (Lengke and Southam 2005).

Added research indicated one of three probable methods by which generation of iron sulfide, selective reducing actions, or a metabolic process are all possible ways that the sulfate-reducing bacteria will reduce the gold (I)-thiosulfate compound. The deposition of gold (I)-thiosulfate is essential in the initial stage, onto recently generated iron sulfide surfaces sulfate-reducing bacteria, resulting in the production of elemental gold. During the second step, using microbes that reduce sulfate will discharge through the outer membrane pores causing the hydrogen sulfide (HS-) to decrease the gold (I)-thiosulfate complex, which led to the precipitation of atomic gold. In the third step, the gold (I)-thiosulfate complex was broken down into the cells that liberate Au(I) and thiosulfate ions (Lengke and Southam 2005; Lengke et al. 2006).

## 13.8 Magnetic Nanoparticles Made by Microbes

There are numerous applications for the magnetic nanoparticle termed as magnetosomes, generated by magnetotactic bacteria (MTB), known as the bacterial magnetic nanoparticle (BMP) (Vargas et al. 2018). These are internal magnetic particulates composed of iron oxides and sulfides that work as bacterial compass needles to direct bacteria through oxygen variations in aquatic environments under the impact of Earth's geomagnetic. BMPs are typically transported by phospholipid vesicles and have the potential to spread in underwater mediums.

BMP biomineralization happens in several stages; the cytoplasmic membrane is invaded by a GTPase in the first stage, followed by building a linear chain throughout the cytoskeletal filaments. The second stage includes the accumulation of ferrous ions using transmembrane iron carriers within the vesicles. The third phase involves the induction of BMP proteins, which results in the gradual buildup of supersaturating iron levels and the fractional reduction and dehydrating of ferrihydrite to magnetite (Arakaki et al. 2008).

*Shewanella oneidensis* produced magnetite using passive and active methods in a different investigation. In a high-pH environment, ferrihydrite is actively used to produce $Fe^{2+}$ as a supply of electron acceptor. The transition of Fe2+ and Fe3+ adjacent to negative-charged cell walls occurs next, which causes supersaturation and the precipitation of magnetite (Li et al. 2011). This membrane controls the thickness, crystallization, and shape of the particle. The phospholipid bilayer, which has 20–40 different surface protein species, can capture bacterial nanoparticles (Grünberg et al. 2004).

Although additional MTB species can be grown, the BMPs utilized in nanobiotechnology and nanomedicine are primarily derived from *Magnetospirillum magneticum* AMB-1 and *Magnetospirillum gryphiswaldense* MSR-1 (Chen et al. 2016).

## 13.9 Stable Quantum Dot Nanoparticles Made by Microbes

A wide range of biological, biomedical, optical, and optoelectronic application domains, including biosensors, photovoltaics, transistors, oil exploration, biomedicine, imaging, and solar cells, are recently becoming increasingly dependent on fluorescent or quantum dots (QDs) nanomaterials. This is because of their unique size-dependent characteristics. According to improved biocompatibility and lower production of harmful byproducts during their synthesis, they are more practical, pointing the way toward environmentally friendly technologies. Bidentate thiols, such as dithiothreitol (DTT), mercaptosuccinic acid (MSA), and mercaptopropionic acid (MPA), and CdS, CdSe, and CdTe QDs have currently been synthesized using ligands with different functional compounds (amino, hydroxyl, and a carboxylic acid, among others). These cadmium- and tellurite-resistant Antarctic bacteria, *Pseudomonas* (eight isolates), *Psychrobacter* (three isolates), and *Shewanella* (one isolate), may synthesize CdS and CdTe QDs in response to hazardous oxidizing heavy metals like Cd and Te with a time-dependent shift in fluorescence emission color (Plaza et al. 2016). One example of nanomaterials with fluorescent tags is CdSe. In *S. cerevisiae*, CdSe nanoparticles were produced intracellularly by Cui et al. (2009) utilizing genetic engineering methods. When in contact with inorganic ions, in yeast the glutathione production genes GSH1, GSH2, and GLR1 go inactive, which in turn causes a considerable decrease in fluorescence that is inversely correlated with the production of CdSe nanoparticles. It was discovered that Na2SeO3 was converted to selenocysteine $(Cys\text{-}Se)_2$, a selenium compound that comprises cysteine. After that, $CdCl_2$ was used to make CdSe nanomaterials. Halophilic bacteria like *Halobacillus* sp. were investigated in the following investigation by Bruna et al. (2019). DS2 built CdS QDs having improved NaCl resistance (Bruna et al. 2019). Órdenes-Aenishanslins et al. (2020) created a cation exchange-based, adjustable ternary CdSAg QD. By exposing the interaction between bacterial cells with cysteine and CdCl2, nanoparticles were also made extracellularly within the cells of the bacteria. The stabilization of the nanoparticle in this reaction was accomplished by cellular biomolecules and was reliant on the synthesis of $S_2$, which was carried out by enzymes called cysteine desulfhydrases.

## 13.10 The Synthesis of Nanoparticles from Microbial Organic Particles

Nanofibers are created using bacterial cellulose (BC), which is also employed to give the nanofibers a bactericidal quality. In a procedure that is regarded as green, bactericidal chitin (Ch) and bacterial cellulose (BC) nanofibers were combined to create a nanocomposite of BC-Ch. Additionally, Ch79d was fed to *Acetobacter aceti* to create 50–100 nm-wide nanofibrils and biosynthesize bio-BC-Ch79d nanocomposites (Butchosa et al. 2013).

The making of nanoparticles is discovered to involve a variety of microbial elements (Table 13.1). These nanoparticles are proven to operate as effective anti-biofilm agents by inhibiting the QS mechanism.

## 13.11 Quorum Sensing

The process of Quorum sensing is a density-dependent, interaction form of cell to cell communication related chemical substance substitutes (Lobedanz and Søgaard-Andersen 2003; Phelan et al. 2012), chemical signaling (Eberhard et al. 1981), signaling linked utilizing an electrical impulse (Nielsen et al. 2010; Shrestha et al. 2013), is what allows bacterial cells can adapt to and keep track of different circumstances in the environment. Quorum sensing was the term referring to a density-dependent communications medium in bacteria that is caused by tiny chemicals (autoinducers) (QS). *Vibrio fischeri* was the first organism to exhibit this mechanism (Nealson et al. 1970). QS is a word conceptualized by Fuqua et al. (1994).

Its multistep methodology that results in the formation of biofilms involves the manifestation of many different reactions of genes to the same organism's planktonic form of microbial cells (Donlan 2002). The transformation of unicellular organisms into their motile forms causes the production of different chemicals that promote genetic alterations within the cells. As a reaction, microcolonies that are sessile create an extracellular polymer that is dense (EPS) that wraps the bacterial cells physically. Such EPS is composed of exopolysaccharides, proteins, exogenous DNA (e DNA), and other molecular components. Through the quorum sensing process, this situation causes the biofilm to develop QS (Lahiri et al. 2019; Sonawane et al. 2022).

The biofilm structure is caused by the permanent attachment of microbial cells to surfaces, which is preceded by the synthesis of QS particles, mobility of biofilm particles, substrate digestion by diverse sessile microcolonies, the development of EPS, and ultimately spreading of the sessile populations (Lahiri et al. 2019).

The foundation of QS was the production of extracellular substances called autoinducers (AIs), which allow bacterial cells to interact with one another. This technique aids in organizing the many expressions of bacterial cells so they can react to environmental changes. Gram-positive, as well as Gram-negative, bacterial cells exhibit this method. According to studies, Gram-positive microorganisms employ

**Table 13.1** Formation of nanoparticles by microbes

| Classification | Microorganism | Element used | Size of nanoparticles (nm) | Reference |
|---|---|---|---|---|
| Actinomycetes | *Streptacidiphilus durhamensis*<br>*Streptomyces griseoruber* | Ag<br>Au | 8–48<br>5–50 | Buszewski et al. (2018)<br>Ranjitha and Rai (2017) |
| | *Streptomyces xinghaiensis* OF<br>*Rhodococcus* sp. NCIM 2891 | Ag<br>Ag | 5–20<br>10–15 | Wypij et al. (2018)<br>Otari et al. (2014) |
| Fungi | *Penicillium diversum*<br>*Fusarium oxysporum* JT1<br>*Trichoderma harzianum*<br>*Aspergillus terrous*<br>*Colletotrichum* sp. | Ag<br>Au<br>CdS<br>ZnO<br>AlO | 10–15<br>22<br>3–8<br>28–63<br>30–50 | Ganachari et al. (2012)<br>Thakker et al. (2013)<br>Bhadwal et al. (2014)<br>Baskar et al. (2015)<br>Suryavanshi et al. (2017) |
| Yeast | *Rhodosporidium diobovatum*<br>*Saccharomyces cerevisiae* | PbS<br>Ag.Au<br>Nanopiates | 2–5<br>2–20 | Seshadri et al. (2011)<br>Korbekand et al. (2016)<br>Yang et al. (2017) |
| | *Pichia kudriavzevia* | ZnO | 10–60 | Moghaddam et al. (2017) |
| | *Rhodotoruia glutinis* | Ag | 15 | Cunha et al. (2018) |
| Virus | Tobacco mosaic virus (TMV) | Pd.Au | 3–4,5 | Kobayashi et al. (2012)<br>Fan et al. (2013) |
| | M13 virus | $TiO_2$ | 20–40 | Chen et al. (2013) |
| | Hepatitis E virus | Nanoconjugate | 27–34 | Chen et al. (2018) |
| | Potato virus X<br>Muticum | Nanocarriers<br>ZnD | 13<br>0.57 | Le et al. (2017)<br>Sanaeimehr et al. (2018) |
| Algae | *Sargassum amansit*<br>*Gelidium* | Ag<br>Ag | 27–54<br>51 | Pugazhendhi et al. (2018)<br>Kim et al. (2016) |
| | *Laminaria japonica* | Au | 8 | González-Ballesteros et al. (2017) |
| | *Cystoseira baccata*<br>*Chlorella vulgaris*<br>*Spirogyra varians*<br>*Chlorelix vulgaris* | Pd<br>Ag<br>Au | 5–20<br>35<br>2–10 | Garole et al. (2019)<br>Salari et al. (2016)<br>Annamala and Nallomuthu |

(continued)

**Table 13.1** (continued)

| Classification | Microorganism | Element used | Size of nanoparticles (nm) | Reference |
|---|---|---|---|---|
| Bacteria | *Bacillus subtilis*<br>*Lactobacillus* sp.<br>*Lactobacillus* sp. | $TiO_2$<br>$TiO_2$<br>$TiO_2$ | 10–30<br>50–100<br>50–100 | Dhandapani et al. (2012)<br>Ahmad et al. (2014)<br>Ahmad et al. (2013) |
| | *Escherichia coli*<br>*Exiguobacterium aurantiacumm*<br>*Brevundimonas diminuta* | Ag<br>Ag<br>Ag | 5–50<br>5–50<br>5–50 | Saeed et al. (2020)<br>Saeed et al. (2020)<br>Saeed et al. (2020) |
| | *Acinetobacter* sp. SW30<br>*Lactobacillus kimchicus* DCY51<br>*Paracoccus haeundaensis* BC74171<br>*Micrococcus yunnanensis*<br>*Mycobacterium* sp. | Au<br>Au<br>Au<br>Au<br>Au | 15–40<br>5–30<br>$20.93 \pm 3.46$<br>53.8<br>5–55 | Wadhwani et al. (2016)<br>Markus et al. (2016)<br>Patil et al. (2019)<br>Jafari et al. (2018)<br>Camas et al. (2018) |
| | *Lactobacillus* sp.<br>*Lactobacillus sporogenes* | CdS<br>ZnO | 2.5–5.5<br>145.70 | Prasad and Jha (2010)<br>Mishra et al. (2013) |
| | *Lactobacillus fermentum*<br>*Shewanella loihica* | Iron oxide<br>Cu | 10–15<br>10–16+ | Park et al. (2014)<br>Lv et al. (2018) |

autoinducing proteins (AIPs) to communicate, while Gram-negative microorganisms include three major groups of AIs (Raffa et al. 2005). Quorum quenching (QQ) is a method for inhibiting the QS system (Dong et al. 2002). Multiple techniques, including competitive inhibition and QS output cleavage, are required for the QQ process.

From *Bacillus* sp. bacterial quorum sensing (QS) utilizes quorum sensor molecules, which were isolated and separated. The quenching of the quorum ability of the nanocatalyst r-AiiA-MNP was assessed following their molecular attachment to their magnetic nanoparticles (MNPs), and it was shown to be successful in reducing QS (Beladiya et al. 2015). The las network is composed of the regulating element las R, which produces the Las R protein, and the *las I* gene, which controls the production of the 3-oxo-C12-HSL chemical messengers linked with the AHL group. The virulence gene is triggered by the LasR/3-oxo-C12-HSL. The rhlR and rhlI genes make up the real system. These further cause the las I system, which is in charge of synthesizing pyocyanin, rhamnolipids, and swarming motilities, to be activated. The las control is the rhl system. Among the other two networks, PQS functions as an intermediary. The PqsA E controls the conversion of 2-heptyl-4-quinolones (HHQ) into 2-heptyl-3-hydroxy-4-quinolone, acting as a precursor for HHQ.

## 13.12 Mechanism of Gram-Negative Microorganism Quorum Sensing

The messenger molecules known as autoinducers (AI), such as acetyl homoserine lactone (AHL) and additional compounds whose formation is reliant upon S-adenosylmethionine (SAM), were employed by Gram-negative bacterial cells to interact (Walker et al. 2011). SAM functions as an amino acid remover necessary for the synthesis of acyl-homoserine lactones (Whitehead et al. 2001). According to a report, SAM is needed for the manufacture of N-(3-oxo octanoyl)-L-homoserine lactone in *E. coli* via plasmid-associated Lux I (Hanzelka and Greenberg 1996).

The cell membrane's outer layer isn't a barrier to the AIs generated by the bacterial cells. High cell density (HCD) causes an increase in AIs, which controls the regulatory elements for the proteins linked to the QS process. Numerous messenger molecules, such as 2-heptyl-3-hydroxy-4-quinolone from *P. aeruginosa* and 3-hydroxy-palmitic acid from *Ralstonia solanacearum*, are linked to the Gram-negative microbial cells (Flavier et al. 1997). Another one is a nosocomial reactive illness bacterium that is still linked to illnesses such as cystic fibrosis (CF), respiratory infections, and several forms of cutaneous and burned serious infections (Ammons et al. 2009). There are three main QS circuits in these Gram-negative bacteria. One such circuit includes the protein LasR, which codes for the transcriptional regulator LasR, and the protein LasI, which is responsible for producing the autoinducer. Both the gene rhlR, which promotes the transcriptional regulator RhlR, and the protein rhlI, which is involved in the generation of the autoinducer N-(butonyl)-L-Homoserine lactone, make up a significant QS circuit (Pearson et al. 1994, 1995). Alkyl quinolones, particularly 2-heptyl-3-hydroxy-4-quinolones, are linked with the third QS loop, which is also present in P. aeruginosa and predominantly controlled by the pqsABCDEH and PqsR activator proteins (Pesci et al. 1999).

## 13.13 Quorum Sensing Suppression by Microbiogenic Nanoparticles

The capacity of NPs to stop the proliferation of microbial cells and hence combat harmful organisms makes them the most often used drug delivery system. NPs have a variety of inhibitory mechanisms for microbial and biofilm growth. Numerous

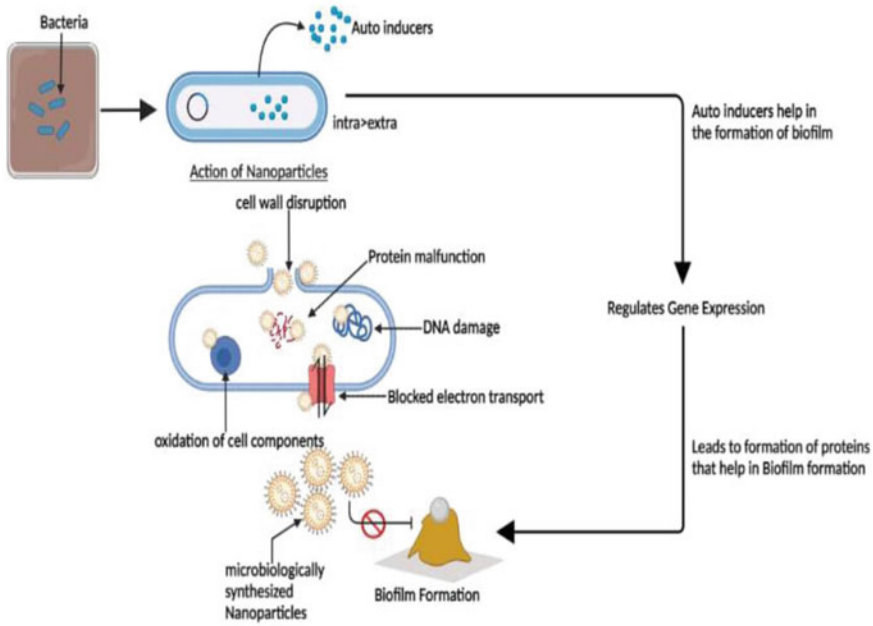


**Fig. 13.1** Nanoparticles synthesized from microbes and their role in biofilm inhibition

investigations were carried out to figure out the most likely method by which the NPs might prevent microbial growth (Fig. 13.1).

Due to the small number of research that has been conducted, information about the reduction of the QS procedure by NPs is quite restricted, despite the field's potential being intriguing. By interfering with the medium of cell-cell interaction or by muzzling the stimuli connected to the QS system, NPs function as strong inhibitors of QS. As a result, they hamper the production of numerous signaling elements and prohibit the synthesis of molecule-receptor complexes. As a result, the signaling molecules loop is stopped (Sadekuzzaman et al. 2015); due to their potent antibacterial action, AgNPs or silver nanoparticles, have been used as QQ regulators (Castellano et al. 2007; Chen and Schluesener 2008).

AgNPs' broad range of antimicrobial properties (Kim et al. 2007; Lara et al. 2011; Brandt et al. 2012), ease of action due to their physicochemical properties, and surface area to volume proportion have all piqued the attention of the scientific community (Kim et al. 2007). Other NPs from microorganisms, including AuNPs, TiO2, SiO2, and ZnO, are effective at suppressing the QS system and preventing the formation of the biofilm (Shah et al. 2008; Samanta et al. 2017; Al-Shabib et al. 2018).

## 13.14 Quorum Sensing Suppression by Silver Nanoparticles (AgNPs)

Ever since the dawn of time, people have been aware of the antibacterial characteristics of noble metals. Silver compounds, metallic silver, and salts have all been used to successfully inhibit microbial development since antiquity. Silver nanoparticles (AgNPs) were created, thanks to advancements in nanotechnology, and because of their huge surface area-to-volume proportion, they demonstrate excellent antimicrobial activity against several pathogenic infections. Multiple investigations have shown the efficacy of AgNPs against both multidrug-resistant bacterial biofilms and planktonic bacterial cells.

AgNPs have a significant surface area to volume proportion, a neutral nature, configurable physical parameters like size and shape, and biocompatibility and have shown bactericidal or bacteriostatic activities at very low concentrations, among other benefits for anti-biofilm applications. Directly acting as an antibacterial agent are AgNPs and the silver ions (Ag+) are produced when AgNPs dissolve. Multiple elements of both unicellular microbial species and biofilms can interact with both AgNPs and Ag+ ions. They hinder bacterial metabolism and exterior cellular operations through these interactions. AgNPs' overall antimicrobial effect is a result of a mixture of cell membrane breakdown, specific proteins dislocation, cellular membrane downregulation, protein denaturation, blocking of the electron transport chain (ETC), oxidative stress brought on by the generation of reactive oxygen species (ROS), impairing of nucleic acids, and oxidative stress itself (Gupta et al. 2018; Prasad et al. 2017).

Furthermore, it has been shown that green-synthesized NPs were crucial in preventing infections brought on by microorganisms. According to studies, AgNPs may prevent the production of messenger elements by suppressing LasI/Rhl I synthase. AgNPs may inhibit *P. aeruginosa*'s quorum sensing (Ali et al. 2017).

The reduction of silver nitrate solution using *Azadirachta indica*-mediated leaf extract to produce silver nanomaterials. Gram-positive *Staphylococcus aureus* and model Gram-negative *Escherichia coli* bacteria were utilized to examine the antimicrobial activities of the generated AgNPs. The zone of Inhibitory activity against *S. aureus* and *E. coli* was found to be 10 mm and 13 mm, correspondingly, and the biofilm assessment revealed a substantial influence on nanoparticle concentration. The creation of biofilms is necessary for the production and secretion of EPS (exopolymeric substances). In general, bacteria create biofilms and colonize in response to their environment. According to certain findings, 100 nm-sized AgNPs can reduce biofilm activity by 90–95%. According to certain publications, biofilm development has become more distinct as the number of nanoparticles has increased. This indicates that microorganisms can withstand the toxicity of nanoparticles and may provide better remediation in the future. AgNPs generated extracellularly by *Cedecea* sp. stand out for their exceptional physical stability, which results in unabated antibacterial activity for periods longer than a year.

AgNPs can lock the reactive groups of numerous molecules, including LasI or RhlI synthase, as well as their neighboring groups being available, according to *in* *silico* investigations employing molecular docking. AgNPs successfully block the reactive sites and strongly inhibit the quorum sensing (QS) process. AgNPs can disrupt the transcriptional factors that inactivate the LasR or RhlR mechanism, hence lowering the activity of the QS proteins. AgNPs can also successfully block messenger molecules like LasI and RhlI so that they are acting anti-QS agents. Studies have also revealed that *Rhizopus arrhizus* metabolites used to generate AgNPs in microfabricated forms hinder *P. aeruginosa*'s QS system (Singh et al. 2015). At a dosage of 0–25 g/ml, it was demonstrated that these microfabricated AgNPs could significantly lower the synthesis of signaling molecules. Furthermore, it has been shown that these nanostructured NPs can downregulate the action of the lasA and lasB proteins up to 79–84%. The AHL-LasR complex induces the action of the specific QS elements, including lasA, lasB, lasI, lasR, rhlI, rhlR, rhlA, phzA1, and fabH2. The nanostructured AgNPs were successful in lowering the activity of the QS genes.

Contrary to what researchers observed about the effects on planktonic cells, it has been observed that *V. vinifera* cane extract inhibits the metabolic activity of biofilm cells. The greatest extract concentration (2% (v/v)) reduced metabolic activity by 32% relative to the control. Similar to how they affected planktonic cells, polydisperse AgNPs were more successful in reducing the activity of the cells that make up biofilms. At a dosage of 20 mg/L pAgNPs/e, the strongest reduction in metabolic activity (80% relative) was noted. Less than 50% metabolic activity was reduced in the biofilm cells by the monodisperse AgNPs (20 mg/L).

*Cyperus esculentus* extracts were effectively employed as efficient reductants in the work by (Ajayi et al. 2015) to create silver nanomaterials. In these methods, *Cyperus esculentus* extracts are made by crushing and spending a lot of time incubating. The outcome shows that the produced particles are active in avoiding biofilm formation, improving the efficiency of antibiotic and antifungal drugs through synergistic interactions, and suppressing microbial growth.

## 13.15 Quorum Sensing Inhibition Using Microbiogenic Gold Nanoparticles

Due to its straightforward manufacturing process, ease of usage, and relative lack of toxicity when compared to other commonly used nanomaterials, Au NPs have several uses (Capek 2014). *Salmonella typhi*, Bacillus Calmette-Guerin, and methicillin-resistant *S. aureus* (MRSA) are just a few of the bacteria that Au NPS effectively combated (Zhao et al. 2010; Lima et al. 2013; Bindhu and Umadevi 2014). Investigations have demonstrated that the acyl-homoserine lactone lactonase enzyme connected to gold NP involves in preventing *Proteus* sp. quorum sensing (Vinoj et al. 2015). N-acyl-homoserine lactonase that was present on their surface helps in the breakdown of N-hexanoyl-L-homoserine lactone.

Additionally, the proteobacterium *Shewanella oneidensis* MR-1 was used to biogenically synthesize gold-silver bimetallic nanoparticles. These particles demonstrated antibacterial characteristics and were used to prevent the biofilm formation of *P. aeruginosa*, *S. aureus*, *E. coli*, and *Enterococcus faecalis* cultures at a dosage of 250 μM. (Ramasamy and Lee 2016).

Hence, they were able to limit EPS generation and metabolic processes, which prevented the development of biofilm and altered the microbial cells' hydrophobicity (Samanta et al. 2017). The consistency of the NPs, which in turn played a considerable impact in decreasing pyocyanin synthesis from *P. aeruginosa*, was brought about by the Au NP formed from Laccaria fraternal's mycelium (Samanta et al. 2017).

## 13.16 Quorum Sensing Suppression by ZnO Nanoparticles

Green synthesis sometimes referred to as biosynthesis, is a natural process of creating ZnO NPs that employ microorganisms as the reducing agents. These microorganisms include algae, fungi, yeast, bacteria, and plant extracts (Bhuyan et al. 2015; Kavitha et al. 2023). Even if utilizing microbes as reducing and stabilizing agents during the manufacture of ZnO nanomaterials has its advantages, more vigilance is used due to the virulence of some microorganisms and incubation problems. Rhizosphere microorganisms called plant growth-promoting microbes (PGPMs) can invade the root habitat. Among the microorganisms that are present in this region are fungi and bacteria that can enter the soil around the roots and rhizosphere. Some *Trichoderma* species that have been shown to interact symbiotically or as endophytes with plant roots are included in the group of fungi that promote plant growth (PGPFs). Numerous studies on *Trichoderma* as a biological control agent, biofertilizer, fungicide, and plant development booster have been conducted (Prasad and Rai 2023). The therapeutic capacity of *Trichoderma* compounds has, however, received scant attention.

*Trichoderma* spp. was chosen to biosynthesize ZnO NPs and examine their antimicrobial efficacy against the human diseases *S. aureus* and *E. coli* along with their ability to prevent biofilm formation (*S. aureus*) when used at various ZnO NP doses. Using a 96-well microplate, the anti-biofilm abilities of ZnO NPs and tetracycline were assessed. Planktonic *S. aureus* treated with reagents for 24 h at a time was examined for biofilm formation inhibition. An established crystal violet assay for biofilm biomass revealed that ZnO NPs were highly effective than tetracycline at removing the formed biofilm generated by *S. aureus*.

In a *P. aeruginosa* colony obtained through cystic fibrosis (CF; García-Lara et al. 2015), the quorum sensing (QS) mechanism's suppression had a significant impact on the biofilm's development. The QS elements within Gram-negative microbial cells can be downregulated by these NPs. Researchers demonstrated that downregulating lasR, lasI, rhl I, and rhl R allowed ZnO NPs to block QS in *P. aeruginosa* (Saleh et al. 2019). Additional research demonstrated the efficacy of ZnO NPs inhibiting the pqs and las mechanism of QS as well as their ability to decrease the floating and clumping motility of *P. aeruginosa* (Khan et al. 2020). ZnO nanoparticles caused the production of the pyocyanin-associated phz operon to be repressed as a consequence of the efflux of the zinc ion efflux pump of the czc operon and various other transcriptional activators, including the porin protein opdT and type III inhibitor ptrA. Additionally, *P. aeruginosa*'s membrane hydrophobicity can be increased by the ZnO NPs (Lee et al. 2014).

## 13.17 Quorum Sensing Suppression by Various Other Nanoparticles

Other nanomaterials from microbial sources, including AuNPs, $TiO_2$, $SiO_2$, and ZnO, are effective against the QS technique and prevent the production of the biofilm (Shah et al. 2008; Samanta et al. 2017; Al-Shabib et al. 2018).

According to experimental results, AgCl-$TiO_2$ nanomaterials were an excellent anti-quorum sensing material that inhibits violaceum (Naik and Kowshik 2014). Additionally, it has been observed that the silver in Ag nanomaterials can stop the development of violacein, which can specifically disrupt the QS process. Additionally, AgCl-$TiO_2$ NPs were shown to block QS even without having oxo-octanoyl homoserine lactone.

Studies have demonstrated that NPs covered with cyclodextrin help in the suppression of *V. fischeri*'s AHL-dependent QS (Miller 2015). According to the research, having cyclodextrin in combination with Si-NP is utilized in removing the AHL compound from the surrounding and lowering bioluminescence. Further research revealed that these NPs can suppress the LuxA and LuxR proteins.

## 13.18 Conclusion

Quorum sensing, which involves examining the synthesis of autoinducers, allows microbial organisms to detect the presence of other organisms in their environment. The formation of a biofilm is facilitated by this process, which also enables bacterial cells to interact with one another. The major modes of action of QS inhibition include signal receptor blockade, inhibition of messenger production, and interrupting the QS pathway. At the moment, the topic is concentrated on developing chemicals with microbial origins to stop the bacterial QS mechanism. Infections related to medical implants are more frequently caused by microbial biofilm. Therefore, the need for innovative treatment methods for infections caused by device-associated biofilms is critical. By removing the exopolysaccharides (EPS) of the biofilm membrane and eliminating the pathogen, the usage of nanomaterials has developed as a successful tactic for preventing biofilm development. Nanomaterials' low cytotoxicity and unique modes of action are major considerations in their use for biofilm therapy. Physicochemical characteristics of nanoparticles, like their dimensions, shape, surface properties, organization, aggregation status, and cellular components under interaction with the nanomaterials, all have a significant impact on how poisonous they are. The time-consuming methods involved in purification and our limited understanding of the mechanics are the few drawbacks of microbial nanoparticle manufacturing. Furthermore, it is crucial to manage the dimensions, forms, and monodispersity of the solution phase. Building up production-level manufacturing for commercial purposes is a significant task. Therefore, it is necessary to address several crucial situations, which include determining the best organism based on their development rates, metabolic activities, and biosynthetic pathways, selecting the catalytic state (microbial proteins), that can either be complete cells, unprocessed proteins, or purified compounds and can speed up reactions, and finding the better environments for cell development and metabolic activity. Maximum biomass synthesis, appropriate reaction circumstances for improved elimination of undesirable excess substances and byproducts, enhanced extraction and separation processes (freeze-thawing, heating processes, and osmotic shock) of the nanoparticles, and improved containment of the generated NPs without accumulation. A novel chemical that may be utilized to downregulate the operon linked to quorum-sensing genes or boost quorum-quenching action to avoid biofilm formation. Anyhow QS suppression has a lot of promise as an anti-infective, further study and research are required to help in understanding the nature of its action and therapeutic relevance. Although there is still a requirement for further advances to avoid regrowth following biofilm therapy, it is anticipated that nanomaterial-based treatment approaches will continue to develop more complicated or sophisticated processes of removing the EPS and destroying the microorganism.

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