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Microbial nanomaterials: Role in sustainable agricultural practices

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ABSTRACT

The increased use of chemical fertilizers, pesticides, soil-based heavy metals to improve productivity in agriculture results into higher pollution level in agroecosystem. It has become a major issue on a global scale that seriously jeopardizes people's health and welfare as well as affects society and overall economy. In view of this, there is an urgent need to detect pollutants in the agroecosystem so that remediation practices can be implemented in time. The evolution of more responsive, affordable and precise technology is needed to create nano-sensors or nanodevices that can be used to monitor agricultural pollution, and the processes involved in pollution control. Major focused ones are those that can detect pollutants at very low concentration levels, as well as point-to-point sensing, *in situ*, and uninterrupted monitoring devices that offer synchronized data. These sensors are readily available in the market for the detection of organic pollutants, gases, volatile organic molecules, heavy metal ions, hazardous metal ions, etc. but they consume a lot of power and lack sophisticated technologies for improved selectivity and sensitivity. Their precision, sensitivity, response speed and environmental stability under actual operating conditions can all be improved with the aid of nanotechnology. In this study an attempt was made to describe how microbial biosensors can be used to detect toxic materials in agroecosystems. Additionally, an application of nanomaterials as pesticides and antimicrobial agent has also been discussed.

Keywords: Inhibition, Microbial nano-materials, Micro-organisms, Nanoparticles, Sustainable agriculture, Toxic substances

The current agricultural methods used to produce food include indiscriminate agrochemicals, advanced machinery, and unchecked resource consumption. These techniques have caused the soil, air, and water resources to deteriorate significantly, expressly raising pollution levels in agricultural ecosystems, which in turn have negatively impacted human and animal health. It is a serious issue that deadly hard-core rocks like Cadmium, Copper, Zinc, Mercury, Lead, and Chromium are still present in agroecosystems because it is believed that they have harmed numerous biotic systems significantly and permanently by interfering with biological processes at the cellular level. These include photosynthesis, mineral absorption, the respiratory chain, and the initiation of peroxidation of lipids, by causing oxidative stress, altering the metabolism of vital nutrients, and different plant organs including the roots, and leaves being harmed (Sharma *et al.* 2021). In essence, a biosensor is a tool of analysis used to measure target particles in samples. In most cases, it includes a bio-recognition component (such as an aptamer, antibody, enzyme, etc.) that is unique to the target. The transducer converts the physiological, chemical, or biological signal into a quantifiable quantity as a result of molecular recognition interconnection between the identification component and the target particles. Electrical and optical signals like colorimetry, luminescence, and SPR (Surface Plasmon Resonance) are used to display signals, while voltammetry, impedance, and capacitance fall under electrical signals (Nithiranjan *et al.* 2018). Systems that are biologically recognized like foreign substance immunoglobulin, active site, substrate specificity, and complementary genetic code orders are often employed. Depending on the signal transduction method, biosensors can be classified as electrochemical, optical, piezoelectric or magnetic (Kundu *et al.* 2019). Sustainable food production has made extensive use of electrochemical impedance spectroscopy-based biosensors, which detect the frequency of the current response by applying a tiny voltage to the perception electrode. Impedance biosensing devices have the potential to become mobile sensors for environmental management and research because they are entirely electrical in nature (Nithirajan *et al.* 2018). The connection between the elements and the sensors must be close and steady in regulating the signal from the identification component to the amplifier. A dependable microbial biosensor must include

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the microorganisms in the sensor as a basic necessity. The degree of immobilization affects the microbial biosensor's ability to be reused as well as the condition of the signal that is delivered from the microbes to the sensor. As a result, immobilizing is crucial in creating a microbial biosensor. Traditional techniques like cross-linking, covalent binding, trapping and adsorption are used for immobilization. Nevertheless, these techniques have issues with one being inferior continuing stability and the other being bad reactions to strong reaction conditions. By utilizing nanomaterials like nanoparticles, nanotubes, and fiber optics, which support increased reliability and stability of the elements, advances in nanotechnology offer a substitute for better immobilization (Kumari *et al*. 2022, Saxena *et al*. 2022, Stephen *et al*. 2022, Siddiqui *et al*. 2023). Another crucial component of the microbial biosensor that transforms the biological processes into a quantifiable wave is the transducer. Biosensors will be utilized in smart monitoring to stop pests and illnesses that could affect agricultural products from impacting food quality, and safety along with biochemical and other forms of contaminants. Additionally, things like alcohol, carbs, acidic chemicals, etc. can also be measured with biosensing devices (Ukhurebor 2020).

Toxic materials encountered in agricultural practices

Fungi have both beneficial and harmful effects in agriculture (Saxena *et al*. 2015). The application of pesticides in agricultural fields helps in preventing, controlling, or eradicating weeds, fungi, and other pests to improve agroecosystem productiveness. Heavy metals including Cd, Pb, As, Hg, Cr, etc. exert deleterious effects on plants. Cd shows leaf chlorosis, necrosis, root browning, leaf rolling, and reduction in seed germination rate. Pb exposure inhibits seedling growth, root length, and leaf expansion. As induces wilting of leaves, chlorosis, and reduction in seed germination. Hg mediates hypertrophy of root, reduces seed germination, and inhibits biomass production. Cr exerts chlorosis, necrosis, and retardation in growth (Rashid *et al*. 2023). In binding sites, heavy metal ions can take the place of cations, enzyme inactivation, and reactive species generation that causes damage to DNA, breakdown of protein, and oxidation of amino acids. It is generally known that antioxidants can decrease and even inhibit reactive species in addition to binding heavy metal ions (Paramo *et al.* 2020). The different types of toxic materials encountered in agroecosystems are mentioned in Table 1.

Microbial nanoparticles used in the agricultural sector

The creation of nano-sensors has a wide range of possible applications for keeping track of environmental stress and strengthening plant defences against disease. Agrochemicals can be delivered effectively thanks to nanoparticles' (NPs) wide surface area, ease of attachment, and quick mass transfer (Shang *et al.* 2019). Ascomycetes and imperfect fungi, as well as other fungal species, have a tolerance for heavy metals and are able to both internalize and bioaccumulate the metals. Therefore, during the synthesis of NPs, these organisms have been employed for reduction and stabilization. Furthermore, it is quite simple to cultivate fungus on a wide scale, which can be utilized to create nanoparticles that are consistent in size and shape (Guleria *et al*. 2023, Gupta *et al*. 2023, Saxena *et al*. 2023). Yeast cells are truly another important agent for heavy metal bioremediation. Yeasts can remove a variety of heavy metals and are simple to cultivate on inexpensive media (Ali *et al.* 2020).

Nanoparticle production from microbial strains

Although high-purity nanoparticles of the desired size have been produced using physicochemical methods, which are frequently costly and demand hazardous kinds of stuff. The associated toxicity increases significantly when these nanoparticles engage directly with the human body. One of the goal of nanotechnology is to establish an environmental friendly production system capable of producing nanoparticles with low toxicity. To accomplish this goal, several researchers have concentrated their attention on biological processes because they are quick, affordable, and environmentally friendly. As a result, a diverse range of natural microorganism species is involved in the biological production of nanoparticles (Saxena *et al*. 2014, Saxena *et al*. 2016, Saxena *et al*. 2017a,b, Bhatt *et al*. 2018, Ghosh *et al.* 2021). Environmentally favourable catalysts for bioremediation and material synthesis can be discovered in metal-reducing bacteria. In reality, through respiration mechanisms, bacteria may aid in the creation of certain metal oxides (Kim *et al.* 2018). Recent research has shown that *Phalces brevis* produced silver nanoparticles (AgNPs) exhibit exceptional antibacterial capabilities against *Staphylococcus aureus* (Saravanan *et al.* 2018). The colour of the gold nanoparticles (AuNP) containing colloidal solution varied dramatically when *Acinetobacter* spp. SW30 was treated with different concentrations of gold chloride and cell densities. Surprisingly, monodispersed spherical gold nanoparticles of size 19 nm were seen at the lowest cell density and $HAuCl_4$ salt concentration, but increasing cell density led to polyhedral AuNP (39 nm) synthesis. Both amide groups and amino acids contribute to the reduction of gold salt and the stabilization of AuNP (Wadhwani *et al.* 2016). Metal detoxifying and stressors from the environment protection may help organisms, while certain types of nanoparticles can function as nanozymes, regulating redox reactions and catalysis, impacting iron segregation and organic matter deterioration, and offering safety from reactive oxygen species (Yu *et al.* 2020, Meng *et al.* 2020, Chi *et al.* 2021). Table 2 lists some of the different bacterial strains employed in the green manufacture of nanoparticles, whereas Table 3 lists certain fungal and yeast species. The criteria and uses of various nanoparticles are depicted in (Fig. 1).

Mechanistic perspectives

Mechanistic perspective of nanoparticles acting as heavy metal inhibitor: Most nanoparticles accumulate in

Table 1　Different toxic materials encountered in agroecosystem

Class	Toxic material	Source	Effect	Reference
Pesticides (herbicides, insecticides, fungicides)	Organophosphates, Organochlorine (DDT, chlordane), carbamate, neonicotinoids, Toxaphene,	As fertilizers combined with mineral phosphates, manual spraying, mechanical spraying, by surface runoff	Toxic effects on humans by acting as steroid inhibitors and hence affect the nervous system. Affects aquatic as well as terrestrial animals. Persists for a longer time in soil and degrades the soil quality	Carvalho (2017)
Phenols (flavonoids, coumarins, phenolic acids)	Phenolic acids (Benzoic acid, Salicylic acid, Cinnamic acid), Phenolic compounds (Tannin, lignin), acetophenones, phenylacetic acid	Woody parts of plants, coal, shale oil, petroleum, industrial effluents (oil refining, petrochemical production, pharmaceutical production, resin manufacturing), vehicle exhaust, disinfectants	Human health issues like necrosis, digestive problems, and liver as well as kidney damage. Causes air pollution by the formation of nitrophenols (phenols acted upon by UV- radiations). Causes the deaths of many aquatic animals by accumulating in their tissues, hence hampering aquatic environments. Phenolic compounds are non-biodegradable and hence can stay for a longer time in soil affecting the normal useful soil microbiota.	Tutic *et al.* (2015)
Heavy metals	Cobalt (Co), Mercury (Hg), Copper (Cu), Manganese (Mn), Chromium (Cr), Zinc (Zn), Lead (Pb), Cadmium (Cd)	Industrial effluents, upon addition of fertilizers, pesticides, fungicides	High concentration of micronutrients causes toxic effects in plants such as reduced flower, leaf, and pod production. Heavy metals might bind to the active sites of the enzymes inhibiting the normal functioning of enzymes in plants, and animals and ultimately transfering to humans, which can cause DNA damage, and protein degradation.	Paramo *et al.* (2020)
Pathogenic bacterial and fungus	Bacterial and fungal toxins	From soil, contaminated waters, industrial effluents	These bacterial and fungal toxins damage the plant and hence retard the plant growth, and sometimes use up the essential nutrients for their growth, and in turn, the plant does not get the required nutrients for their growth.	Boroumand *et al.* (2015)

Table 2　Different bacterial strains used for green synthesis of nanoparticles

Bacteria	Nanomaterial synthesized	Shape and size range of nanomaterial	Application	Reference
Pseudomonas stuzeri	Silicon nanoparticle	3D nanoparticles, 1 to 100 nm	nano fertilizers, nano pesticides and antimicrobial	Shang *et al.* (2019)
Desulfovibrio desulfuricans	Gold nanoparticles	3D nanoparticles, 1 to 100 nm	antimicrobial and nano fertilizers	Shang *et al.* (2019)
Moorella thermoacetica	Zinc sulfide nanoparticles	3D nanoparticles, 1 to 100 nm	Increases the nutrient uptake efficiency, promotes the root and shoot elongation, acts as nanofertilisers,	Shang *et al.* (2019)
Klebsiella aerogenes	Cadmium sulfide nanoparticles	3D nanoparticles, 1 to 100 nm	nanopesticides and nanofertilizer	Shang *et al.* (2019)
Acinetobacter calcoaceticus	Silver nanoparticles	Spheroidal, uniform nanoparticles, 20 to 100 nm	antimicrobial and nanopesticides	Ali *et al.* (2020)

Contd.

Table 2 *Contd.*

Bacteria	Nanomaterial synthesized	Shape and size range of nanomaterial	Application	Reference
Bacillus amyloliquefaciens	Silver nanoparticles	Spheroidal, uniform nanoparticles, 20 to 100 nm	antimicrobial and nanopesticides	Ali *et al.* (2020)
Bacillus megaterium	Silver nanoparticles	Spheroidal, uniform nanoparticles, 20 to 100 nm	antimicrobial and nanopesticides	Ali *et al.* (2020)
Bacillus licheniformis	Silver nanoparticles	Spheroidal, uniform nanoparticles, 20 to 100 nm	antimicrobial and nanopesticides	Ali *et al.* (2020)
Lactobacillus sp.	Silver nanoparticles	Spheroidal, uniform nanoparticles, 20 to 100 nm	antimicrobial and nanopesticides	Ali *et al.* (2020)
Pseudomonas rhodesiae	Silver nanoparticles	Spheroidal, uniform nanoparticles, 20 to 100 nm	antimicrobial and nanopesticides	Ali *et al.* (2020)
Stenotrophomonas sp.	Silver and gold nanoparticles	Spheroidal, uniform nanoparticles, 20 to 100 nm	antimicrobial and nanopesticides	Ali *et al.* (2020)
Bacillus subtilis	Gold nanoparticles	Nanoparticles, 1 to 100 nm	antimicrobial and nanopesticides	Ali *et al.* (2020)
Shewanella loihica	Platinum nanoparticles	Nanoparticles, 2 to 7 nm	nanofertilisers and nanopesticides for better plant growth	Ali *et al.* (2020)
Bacillus cereus	Silver nanoparticles	Spheroidal, 18 to 39 nm	antimicrobial and nanopesticides	Ali *et al.* (2020)
Pseudomonas poae	Silver nanoparticles	Nanoparticles, 19.8 to 44.9 nm	antimicrobial and nanopesticides	Ali *et al.* (2020)

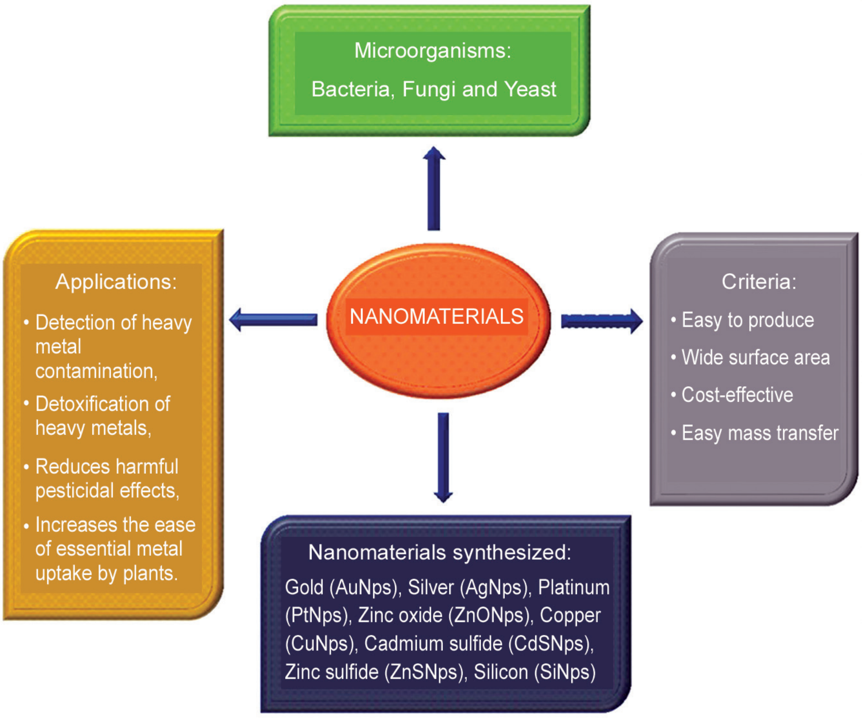

Fig. 1 Source, applications and criteria of nanomaterials.

cell walls, attach to heavy metals, and form complexes that render heavy metals inert. These complexes are adsorbed on the cell surface, which limits the passage of heavy metals in plants and lowers their biological activity (Cui *et al.* 2017, Wang *et al.* 2021). Furthermore, organic acids that have collected in the cell walls of plant roots and leaves can be chelated with heavy metals to reduce the damage caused by heavy metal stress. Exogenous silicon nanoparticles have been found to improve the generation of structural protection agents by promoting the synthesis of organic acids and reducing the harm caused by Cd (cadmium) to plants (Zhou *et al.* 2020). Plant's oxidative defense mechanism can be activated as a further method of reducing heavy metal stress. Plants typically create reactive oxygen species by virtue of particular metabolical processes (Wu *et al.* 2017). For instance, plants continuously create reactive oxygen species in chloroplasts and other cell components during metabolic processes like respiration and photosynthesis. At low concentrations, reactive oxygen species serve as signal molecules for growth, development, and defence (Fig. 2). Excessive reactive oxygen species generation, on the other hand, destroys proteins, cell membranes, and other biological components under stressful conditions (Wu *et al.* 2017). In plants, antioxidant enzymes such as superoxide dismutase, catalase, ascorbate peroxidase, glutathione reductase, glutathione peroxidase, and peroxidase eliminate reactive oxygen species (Zhang *et al.* 2017, Ullah *et al.* 2020, Zhao *et al.* 2020). Stress activates metabolic pathways that are involved in the elimination of reactive oxygen species. For example, galactose, alanine, aspartic acid, and ascorbate metabolism, as well as the formation of shikimate-phenylpropanoid, may alleviate oxidative stress

Table 3 Various fungal and yeast species those are being used in the green synthesis of nanoparticles

Fungi and yeast	Nanomaterial synthesized	Shape and size range of nanomaterial	Application	Reference
Verticillium spp.	Gold nanoparticles	Spheroidal, 20–28 nm	antibacterial, nanopesticides	Boroumand *et al.* (2015)
Aspergillus flavus	Silver nanoparticles	Spheroidal, 8.92 nm	antibacterial, antifungal and nanopesticides	Boroumand *et al.* (2015)
Aspergillus fumigatus	Silver nanoparticles	Mostly spheroidal, sometimes triangular, 5–25 nm	antibacterial, antifungal and nanopesticides	Boroumand *et al.* (2015)
Phanerochaete chrysoporium	Gold nanoparticles	Spheroidal, 10–100 nm	antibacterial agents nanopesticides	Boroumand *et al.* (2015)
Saccharomyces cerevisiae	Silver nanoparticles	Spheroidal, 2–20 nm	antimicrobial and nanopesticides	Ali *et al.* (2020)
Schizosaccharomyces pombe	Silver nanoparticles	Spheroidal, 1–100 nm	antimicrobial and nanopesticides	Ali *et al.* (2020)
Yarrowia lipolytica	Silver nanoparticles	Spheroidal, 1– 100 nm	antimicrobial and nanopesticides	Ali *et al.* (2020)
Pichia jadinii	Gold nanoparticles	Spheroidal, 20–80 nm	Antimicrobial and nanopesticides	Ali *et al.* (2020)

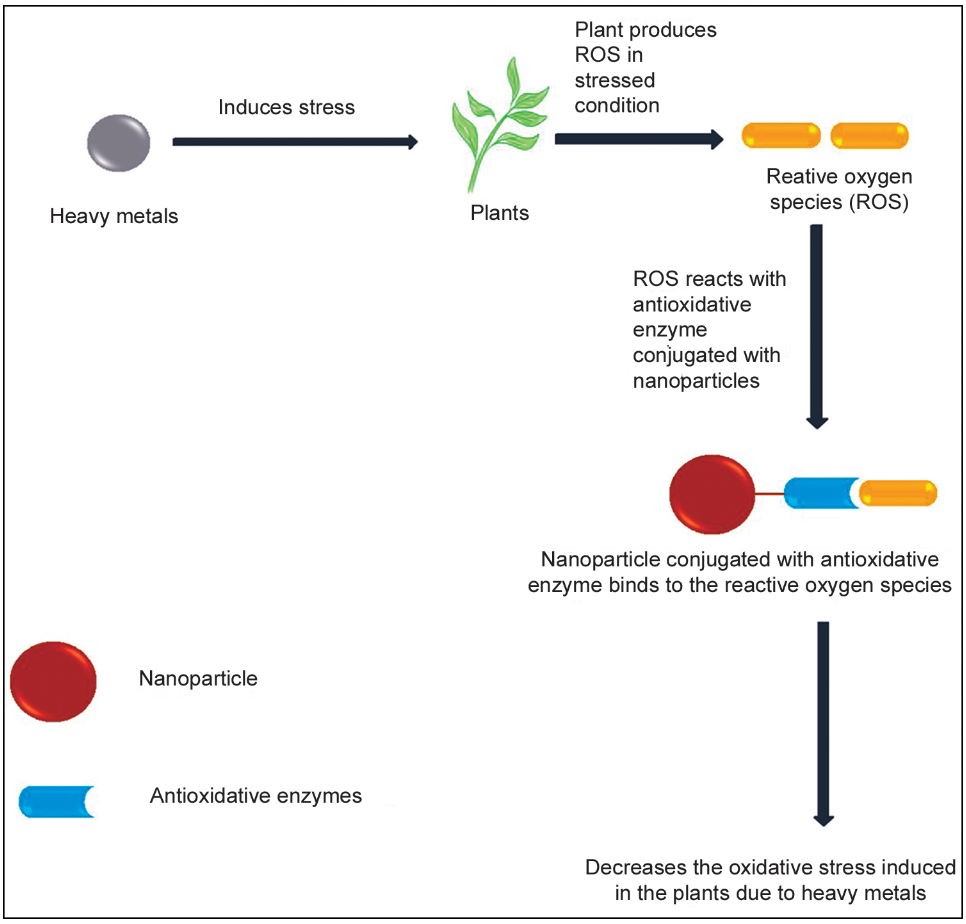

Fig. 2 Mechanism for inhibiting oxidative stress produced by heavy metals using nanoparticles.

in the plant (Lian *et al.* 2020, Hussain *et al.* 2020). As a result, improving plants' ability to reduce reactive oxygen species can reduce crop growth and production losses. Examples of such nanoparticles include cerium dioxide nanoparticles, iron oxide nanoparticles, manganese oxide nanoparticles, and buckminsterfullerene (Wu *et al.* 2017, Konate *et al.* 2017, Yao *et al.* 2018, Guo *et al.* 2019). *Stenotrophomonas acidaminiphila* was employed in a study on a selenium nanoparticle-based agricultural sensor for heavy metal toxicity detection. This study created a colorimetric approach for detecting heavy metals in bioremediation. In the absence of harmful heavy metals, this process occurs naturally, causing reddening. However, when harmful heavy metals are present, the synthesis of selenium green into selenium nanoparticles is prevented, causing the colour to change. This synthesis requires NADH reductase, which gradually deactivates as the concentration of toxic heavy metals increases and causes discoloration (Fig. 3) (Ahmed *et al.* 2020).

Mechanism of nanoparticles acting as nano-pesticides: Pesticides containing organophosphorous (OPs) compounds are the most commonly used in agricultural cultivation. One of the most commonly used OPs, methyl parathion, was

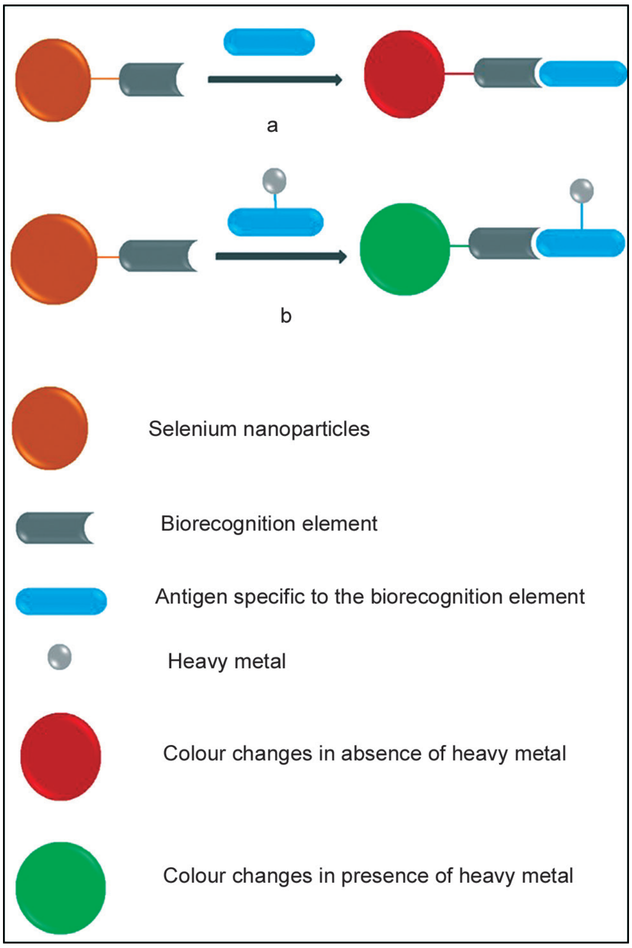

Fig. 3 a. Selenium nanoparticles turn red when there is no-appearance of heavy metals; b. When there is exposure to heavy metals, selenium nanoparticles turn green.

used to manage insect pests in a broad range of products, including fruits, grains, nuts, veggies, and field crops. Because of methyl parathion's ubiquitous and long-term use, quantitative analyses of its residues have garnered a lot of interest. Electrochemical and spectroscopic techniques are used to identify methyl parathion in soils. Carbon nanoparticles' excellent electrical conductivity and large surface area make them perfect for altering electrodes to decrease LODs. Spectroscopic techniques such as being absorbed, luminescence, and Raman spectra, along with electrochemical methods, are frequently used to identify methyl parathion. An effective colorimetric sensor for methyl parathion measurement was created using lanthanum-functionalized AuNPs as a probe. Whenever methyl parathion is mixed with lanthanum, the absorption pattern of AuNPs changes. A colorimetric test can identify methyl parathion in this manner (Zhang *et al.* 2023) (Supplementary Fig. 1). Nanopesticides can influence the pathway of photosynthesis in the biological chemicals or photochemical phases, influencing crop output, based on the physiochemical properties or concentration of the nanoparticles. The mechanical impact of nanoparticles upon plants is proportional to their size and shape, restricting the nanomaterials to specific locations on organ surfaces or within plants. The effects, on the other hand, are capable of being sensed throughout the plant's body, leading to either suppression or stimulation of plant growth. Nanopesticides interact with chloroplasts in the cell's cytoplasm, affecting photosynthetic processes at specific places in plants by binding to and slowing the photosynthetic machinery's function. Studies have shown that metallic nanoparticles are detrimental to photosynthesis by inflicting functional damage to structures (Shekhar *et al.* 2021). Aside from toxicity, the main requirements for NPs utilized as nano pesticides are their chemical composition, shape, surface-to-volume ratio, size, and crystal phase. Nanoparticle-based pesticides frequently outperform conventional pesticides in terms of water solubility and formulation stability, the ability to eliminate harmful organic solvents and gradually release the AI, increased mobility, and insecticidal activity (Chaud *et al.* 2021). Nanopesticides are a new nanobiotechnological product that can encapsulate pesticides for controlled release while also improving pesticide selectivity and stability (Paramo *et al.* 2020, Usman *et al.* 2020). These nano pesticides can provide a variety of advantages, such as improved efficacy, durability, and a need for a less active component in their composition (Kookana *et al.* 2014, Shang *et al.* 2019). Silver nanoparticles (AgNPs), which are among the most researched in biological systems, have long been known for their various inhibitory and antibacterial activities (Chhipa 2017). Similar capping and lowering actions are produced during AgNP production by *Lactobacillus acidophilus* (Rajesh *et al.* 2015). Gold nanoparticles are frequently employed in agriculture as antifungal and antibacterial agents, delivery mechanisms for fertilizer and pesticide sensors, and other uses (Markus *et al.* 2016). Probiotic bacteria can produce cadmium sulphide nanoparticles that can be used as nanosensors. Nanosensors can measure soil moisture and nutrient levels in addition to detecting pesticide residue (Riaz *et al.* 2020). CuNps have many antibacterial and antifungal activities, due to which it has made a remarkable place in the agroecosystem (Kasana *et al.* 2016). Selenium nanoparticles must be provided to the plant to activate antifungal properties and enhance the plant's capacity to fend off infections in order to balance Se in food and alter the Se content in plant nutrients by incorporating selenium fertilizer into the soil (Keiliszek 2019). Despite the differences between each MtNP, the use of nanoparticles in fungicides and pesticides is essential due to their shared qualities, including action against bacteria, cytoplasmic membrane, cell wall disruption, disruptions in the energy and electron transport chains, oxidation of DNA/proteins or harmful ROS generation, and enzymatic inhibition (Bahrulolum *et al.* 2021). For instance, electrostatic interactions enable AuNPs to accumulate at the cell surface as well as exert their antibacterial effect pertaining to the microbial cell wall (Shaikh *et al.* 2019). The advantage of employing bio-pesticides is that they do not have the negative effects on the environment that synthetic pesticides do, but their impact on pests is slower and more limited than that of chemical pesticides (Rai and Ingle 2012). Antimicrobial polypeptides can be encapsulated to aid in their endocytosis when they are encircled by MtNPS. Metallic nanoparticles from plants and fungi help in regulating polypeptide release into cells and kill insect pests' cells as well (Tarvirdipour *et al.* 2020). The incorporation of medicinal plant repellents in MtNPs allows for regulated release, reduces the amount of toxicity of synthetic pesticides, and provides a vital tool for environmental preservation (Oliveira *et al.* 2018). These characteristics allow nano biopesticides to overcome the drawbacks of synthetic and biological insecticides. The active components can be stabilized and made available through sustained release with the help of nanoparticles, providing long-term effective and sustainable management without the risks associated with utilizing synthetic compounds (Kah *et al.* 2019).

Mechanism of nanoparticles acting as antimicrobial agents: Metallic ions can be produced by chemically oxidizing metals in aqueous solutions. Because NPs have larger surface-to-volume ratios than bulk materials and ability to release additional ions under aerobic circumstances. The ions released from nanoparticle's surface are crucial to the antibacterial activity. Nanoparticles initially adhere because of their modest size to the microbial cell wall at the nanoscale before passing through and engaging with the cell membrane. The ions released by them alter the structure of the cell membrane, causing it to lose its integrity and become more permeable. They ultimately lead to cell death by causing leaking of the contents of the cell. The proton motive force and membrane potential of cells are also impacted by nanoparticles that target the cell membrane. Oxidative phosphorylation is also hindered, and intracellular ATP levels are decreased. Silver particles have a substantial bactericidal impact on microorganisms; however, the bactericidal process is only partly known. According to accounts, Ag+ ions create a powerful bond with crucial molecules' thiol (-SH) linkages, making them inactive. According to research, when microbes are subjected to Ag-based fragments, their DNA replication capacity is reduced (Ahmad *et al*. 2020). Free metal ions interact with carbonyl, amino, phosphate, and sulfhydryl (thiol) groups present, over biological macromolecules such as DNA, proteins, and lipids (Tang and Zheng 2018). Furthermore, protein and enzyme thiol groups interact with metal ions such as Ag+, changing their three-dimensional structure and preventing active binding sites for their substrates (Tang and Zheng 2018). The bacterial cell wall is damaged when proteins on the cell membrane and wall are interfered with Ag. This damages the electron transport chain, which prevents the cells from breathing and growing (Ahmad *et al.* 2017). They engage in interactions that deactivate the cytoplasmic proteins required for ATP generation and have an impact on cellular functions (Yin *et al.* 2020). Most often, silver nanoparticles function by releasing Ag+ ions, which can harm bacterial membranes and impede the creation of DNA and proteins (Supplementary Fig. 2). Similarly, gold nanoparticles' photocatalytic activity enables the development of antimicrobial photodynamic treatment in conjunction with photosensitizers. When near-infrared light (NIR) is present, heat is produced that causes the bacterial cell wall to dissolve (Busi and Rajkumari 2019).

Mechanism of phenol inhibition by microbial nanoparticles: A chemical that may minimize the hazardous molecule 4-nitrophenol in the presence of sodium brorohydride ($NaBH_4$) was created during the extracellular synthesis of gold nanoparticles using *Escherichia coli* K12 at room temperature (Srivastava *et al.* 2013). $NaBH_4$ functions as a donor during the conversion of 4-nitrophenol to 4-aminophenol, preventing the formation of nitrophenolate (as a receptor). When silver/gold nanoparticles are introduced to the reaction mixture as a catalyst, the visible UV spectrum shows that the 4-nitrophenol is rapidly transformed to 4-aminophenol (Gangula *et al.* 2011). When $NaBH_4$ is added to 4-nitrophenol, the colour transforms from pale yellow to brilliant yellow, and eventually goes away due to the creation of 4-aminophenol (Ullah *et al.* 2017) (Supplementary Fig. 3). The extremely dangerous chemical compound 4-nitrophenol is one of the most persistent contaminants in the effluents of many sectors, including the textile and dyeing industries. When ingested through food cultivated in polluted locations, this substance can spread across the environment, soil and water contamination, and have detrimental effects on the liver, blood, and central nervous system. Finding a simple and efficient way to eliminate or decrease non-biodegradable bio-contaminants into non-hazardous items is one of the most pressing issues in agricultural systems and environmental studies. 4-Aminophenol, a valuable and significant substance that doesn't offer the environmental dangers of 4-nitrophenol, is the end result of the chemical reduction of 4-nitrophenol. The harmful triphenylmethane colour malachite green (MG) can be broken down into the less dangerous chemical dimethylamino by the *Deinococcus radiodurans* synthesis system, which produces silver-gold bimetallic nanoparticles with a dimension of 149.8 nm (benzophenone). The easy and quick manufacture of silver-gold double nanoparticles functionalized with proteins from the extremophile *Deinococcus radiodurans* enabled the invention of an environmentally benign approach for removing polyphenyl from wastewater (Drp-Au-AgNPs) (Weng *et al.* 2020). Alkaline circumstances, which promote electrostatic interaction between malachite green molecules and these MtNPs, are also thought to impact the capacity of these functionalized Drp-Au-Ag bimetallic metal nanoparticles to break down and reduce malachite green. A class of polyphenolic chemical dyes known as malachite green is frequently used in fishponds to deter insects and vermin. In addition to the effects that have been proven to be mutagenic and carcinogenic in people, malachite green effluents can have long-lasting hazardous and detrimental effects if they are released into the environment. The inexpensive cost of green malachite, however, still tempts people to use it; therefore, it may be argued that there is an environmental problem. Although polyphenyl compounds can be removed physically and chemically, the capacity of nanoparticles to act as possible catalysts for the absorption and subsequent degradation of polyphenol dyes makes this remediation technique effective and ecologically acceptable (Jia *et al.* 2018).

Conclusion

This review focuses on the roles of different microbial nanomaterials that are being successfully implemented in agroecosystems. There are several methods to apply nanotechnology in modern agriculture to sustain and progress the global economy. The introduction of NPs significantly aids in tackling the different issues brought on by climate change, plant and animal illnesses, and population growth. The growing use of conventional pesticides and fertilizers to improve agricultural yield eventually harms the environment. In comparison to conventional resources, the effectiveness and agronomic efficiency of NPs have greatly increased. When attempting to comprehend the physiological and biochemical processes imposed by plants, nanoparticle-plant interaction is a significant concern. Emerging tools for locating and quantifying NPs in the plant system helps in understanding the change and safety implications in a complex system. Synthesis of metallic nanoparticles using green synthesis technology may be straightforward, efficient, clean, non-toxic, and acceptable to the environment due to its promising economic potential. MtNPs can be efficiently biosynthesized using a range of microbes and plant extracts. Microorganisms can manufacture MtNPs more cheaply than plants, despite the fact that it is easier to synthesize MtNPs using plant extracts. The international community's evolving perspectives on sustainable development, the improvement of environmental conditions, and the decline of hazardous man-made waste all point towards the encouraging green production of metallic nanoparticles and their use in a variety of technologies, including agriculture. Nanotechnology is a critical component of sustainable agriculture, but its full potential for widespread application will be realized only if the ecotoxicity of these nanomaterials is completely understood and properly regulated.

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